THE UNIVERSITY OF ALBERTA

# UPTAKE OF PHOSPHORUS FROM LOWER DEPTHS OF SELECTED ALBERTA SOILS

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Department of Soil Science

EDMONTON, ALBERTA

Spring, 1979

Abstract

The objective of this study was to assess the importance to barley of phosphorus from the lower layers of the soil profile. The study was divided into three phases. The first phase involved a field study of the effects of moisture and application of fertilizer phosphorus on the uptake by barley of soil phosphorus from lower soil layers. The second phase was a study of the ability of barley to obtain phosphorus from the different soil layers under greenhouse conditions. The third phase was a field study of the uptake by barley of soil phosphorus from lower soil layers during different periods of the growing season.

The first phase revealed that between 15 and 30 % of the phosphorus absorbed by barley under field conditions was from depths greater than 15 cm. The addition of fertilizer phosphorus to the upper 15 cm of soil resulted in a decline in the importance of soil phosphorus in the lower soil layers. The amount of phosphorus uptake from lower layers varied from site to site and appeared to be affected by the amount of available soil phosphorus present in the upper 15 cm prior to fertilization. The effect of irrigation on the uptake of phosphorus from lower soil layers was difficult to evaluate because rainfall was high during the period when the irrigation treatment was implemented. However, the data suggest that additional moisture resulted in an increase in the importance of subsoil phosphorus when water was able to move freely through the profile into the subsoil.

The second phase of the study was a greenhouse pot experiment where barley was grown on soil obtained from each of the upper three 15 cm layers at the three sites studied in phase one. Barley was able to absorb between 7 and 15 % as much soil phosphorus from soil of lower layers as from the unfertilized surface soils of the sites studied. The relative ability of the subsoil to supply phosphorus to barley was similar to what had been found in the field study. The study also showed that when available phosphorus was increased through phosphorus addition, barley was able to absorb considerably more phosphorus from the subsoil samples. It was found that extractable phosphorus as measured by the Miller and Axley, and Olsen methods was significantly correlated to the amount of phosphorus that barley could absorb from soil from all depths.

The third phase of the study showed that phosphorus in the subsoil increased in importance through the growing season and constituted between 14 and 25 % of the total phosphorus in the above ground portion of barley at eight weeks after emergence. The results suggest that drying of the upper soil layer (Ap horizon) resulted in an increase in uptake from lower soil layers. Data from the third phase of the study also suggested that barley plants may lose a considerable portion of absorbed phosphorus back to the soil. The implication of this is far-reaching because it would invalidate much of the work done to evaluate phosphorus uptake and fertilizer efficiency where $^{32}P$ was

used as a tracer. Work done with the soils from the plot sites of the third phase also showed that there are major difficulties in determining exchangeable phosphorus, and 'E' values must therefore be regarded as highly empirical measurements.

## Acknowledgements

I wish to thank Dr. J. A. Robertson for his guidance and encouragement throughout the course of this study.

Appreciation is also extended to Dr. G. R. Webster and Dr. S. Zalik, who served on the thesis committee, for their suggestions for improving the manuscript.

I would also like to thank my parents for their encouragement throughout the course of my studies.

And finally, I wish to express my deepest thanks to my wife, Barbara, for her help and encouragement.

This study was funded by the National Research Council of Canada.

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# 1. Introduction

In 1977 approximately 110,000 tons of P205 were purchased in Alberta (Alberta Statistics Yearbook 1977 ). The magnitude of this expenditure makes it imperative that users achieve optimun efficiency of application. At present, determination of P fertilizer requirement is normally based on chemically extractable phosphorus in the upper 15 cm of soil. This approach has not always been entirely successful and it has been suggested that poor correlations between chemically available P and crop reponse to fertilizer P may be a consequence of variable exploitation of the soil by plant roots (Spratt and Rennie, 1962 and Olsen <u>et</u> <u>al</u>. 1954). Spratt and Rennie referred to the change in 'effective availability' of phosphorus in the soils. Racz <u>et</u> <u>al</u>. (1964) defined effective availability as "a function of chemical availability of any nutrient and the volume of soil encompassed by the root". Odynski (1934) stated:

> "Surface sampling alone is inadequate as a means of determining the phosphorus value of a soil. Plant roots feed much below the surface horizon, hence the determination of phosphorus in the subsurface horizons seems necessary to show the amount and forms of phosphorus present for possible utilization as plant food."

Odynski based his statements primarily on his work which had shown that there were considerable quanities of easily soluble phosphate present in the lower horizons of many

Alberta soils and on the work by Weaver (1926) which indicated that roots may penetrate to considerable depths in the soil. Although it has been suggested that the mere presence of roots does not guarantee that they are important in plant nutrition, (Barley, 1970) there is evidence that subsoil phosphorus may be important under certain conditions. Richter *et al*. (1977) found that when the topsoil was low in P, the subsoil could be an important source of P for plant nutrition. Their work also showed that as fertilization increased, subsoil P decreased in importance. Vetter and Fruchtenicht (1977) found that subsoil P and depth of root penetration were important factors in determining the economically optimum phosphate rate.

Keeping in mind the previously mentioned evidence along with the fact that barley is the largest single crop in Alberta, this study was designed to determine:

1. the importance of subsoil P to barley crops as affected by soil Order.
2. the effect of certain management practices on the degree to which a plant exploits subsoil P.

## 2. Review of Literature

Soil fertility can be defined as the nutritional suitability of a soil for the growth of a plant. It is extremely difficult to quantify the factors affecting fertility because interactions between the factors are the rule rather than the exception. In the specific example of phosphorus status of a soil, the level of available phosphorus is not synonymous with the level of phosphorus fertility. Modification of any growth factor may result in alteration of a plant's growth characteristics. This may be expressed as changes in root habit, specifically, the number, efficiency and distribution of roots. These changes may result in considerable modification of the amount of phosphorus available to the plant, which greatly complicates determination of the phosphorus status of soils (Drew and Saker, 1978; Kmoch et al., 1957; Spratt and Rennie, 1962 and Warder et al., 1963).

The purposes of this literature review are:

1. to examine some of the techniques that have been used to investigate the soil-plant relationships with respect to phosphorus fertility.
2. to review relevant work on plant uptake of phosphorus with respect to depth in the profile and factors affecting the importance of phosphorus at different depths.

## 2.1 Evaluation of Phosphorus Fertility

Extensive research has been carried out to evaluate phosphorus fertility status of soils (Alexander,1973; Miller and Axley,1956; Olsen *et al*.,1954; Omanwar,1970 and Robertson,1962). Various methods, such as chemical extraction, isotope techniques and biological uptake have been used. Chemical extractions are the most common because they are more convenient and are suitable for large scale application. Originally chemists approached the problem by trying to develop methods that quantitatively extracted the same form and amount of phosphorus as did the plant roots (Russell,1961). However, this approach was abandoned when it became clear that even if success was achieved the method would be applicable to only one type of plant. The approach now used involves correlation of extractable phosphorus content of a soil to the responsiveness of a given crop to phosphorus addition.

At present the two chemical extraction methods used in western Canada are those of Miller and Axley (1956) and Olsen *et al*.(1954). The Miller and Axley extraction uses a 0.03 M NH4-F + 0.015 M H2SO4 solution. NH4-F dissolves aluminum and iron by its complex-ion formation with aluminum and iron in an acid solution (Olsen and Dean, 1965). The method is considered most suitable on neutral to slightly acidic soils (Olsen and Dean, 1965). Difficulties may arise when it is used on calcareous soils because the acid is partly neutralized, resulting in low values for extractable

phosphorus (Olsen et al.,1954) The Olsen method uses 0.5 M $NaHCO_3$ solution buffered at pH 8.5 and operates by two major mechanisms. The presence of $HCO_3^-$ decreases the activity of $Ca^{++}$ by causing precipitation of calcium as $CaCO_3$. This results in increased solubility of calcium phosphates which are thought to be a major source of plant-available phosphorus in calcareous soils. As well, the $HCO_3^-$, $OH^-$ ions replace phosphate ions from soil sorption sites. Extractable phosphorus by the Olsen method is better correlated with plant response on calcareous soils than is extractable phosphorus by acidic extraction methods (Olsen et al., 1954). This is thought to be because the extraction solution is buffered at a constant pH and is more suitable for extracting calcium phosphates. The method has been shown to give high values of extractable phosphorus on acid soils, probably as the result of increased carbon dioxide pressure in the extraction vessel (Warren and Johnston,1965).

The amount of phosphorus extracted by both methods has been found to be highly correlated with 'A' value measurements of plant-available phosphorus (Olsen et al., 1954; Omanwar, 1970 and Omanwar and Robertson, 1973). As well, extractable phosphorus by these methods has been shown to be highly correlated with yield response. Robertson (1962), in a greenhouse study of 79 Alberta soils, found that the response of barley was highly correlated with extractable phosphorus as measured by both methods. He found correlations ranging from r=0.73** to r=0.79** for the

Miller and Axley method and correlations of r=0.73** to r=0.82** for the Olsen method. Numerous other studies in the greenhouse have shown high correlations between phosphorus extracted by these methods and plant response (Maclean _et al_., 1955; Martar and Samman, 1975; Miller and Axley, 1956 and Olsen _et al_., 1954). However use of these methods to predict crop response in the field has not been so successful. Olsen _et al_. (1954) found that field crops failed to respond to fertilizer phosphorus when extractable phosphorus was at levels that would indicate response in the greenhouse. He postulated that the lack of response occurred because a larger volume of soil is available to plant roots under field conditions. Thus, it was suggested that the total volume of soil utilized by plants must be considered when studying phosphorus status of a soil.

Olson _et al_. (1958) studied the importance of subsoil phosphorus in predicting crop response to fertilizer phosphorus. He found that:

> "subsoil phosphorus test adds some, but not much, to the precision of forecasting phosphorus need by topsoil evaluation alone."

On the sites he studied there was a reasonably close correlation between topsoil and subsoil phosphorus levels. (r=0.63** for individual topsoil versus subsoil phosphorus levels) Olson stated that differential fertilizer treatment may alter the topsoil-subsoil extractable phosphorus correlation. If the correlation is poor, relying on

phosphorus status of the topsoil may result in erroneous conclusions concerning the phosphorus fertility factor of a soil. Correlations between extractable phosphorus in the 0-15 cm and 15-30 cm depths of 48 plots on each of six Alberta sites were variable and lower than those reported by Olson *et al.*[1] The correlations for seventeen site years at the six sites ranged from r=-0.43 to r=0.48. Robertson (1973) has reported that the variability of crop response to the application of phosphorus fertilizer on Solonetzic soils is large and predicting crop response is quite uncertain. Solonetzic soils are more variable in profile characteristics than other agriculturally important soils in Alberta. The toughness of the Bnt horizon and the thickness of the Ah horizon play an important role in altering the root distribution of crops grown on these soils. If subsoil phosphorus is important, one would expect the more anomalous results in phosphorus response to occur on Solonetzic soils.

The previous discussion has indicated subsoil phosphorus probably does play a role in plant nutrition; however these reports offer little information on the degree of importance. As indicated, root distribution is an important factor in determining the importance of subsoil phosphorus . Roots, by their nature, are much more difficult to study than the above ground portion of plants. For this reason it is relevant at this point to examine some of the methods that have been employed in plant

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[1]J.A.Robertson Personal Communication

root investigations.

## 2.2 Root Distribution and Activity

Among the first workers to attempt to study the root morphology of a plant root system was Hales (1727). His method was not greatly different from those employed more recently. He simply washed the soil away from the roots from above. Over the next 250 years other workers introduced different procedures for study of root systems, including the 'soil-containers method', the 'water culture method', the 'trench washing method', the 'steelframe washing method' and the 'observation pit method' (see Pavlychenko,1937). Among the more well known methods is Weaver's trench tracing method. Weaver (1919) described the method as follows:

> "The method employed in excavating root systems was to dig trenches 2 to 3 feet wide and 6 to 10 feet long to a depth of about 6 feet... the trenches were deepened as work progressed...In several cases where the roots extended to depths of 18 or 20 feet or more, the soil was removed by means of a bucket attached to a rope...Considerable danger from caving was experienced, especially in the sandhill soils...Drawings were made simultaneously with the excavating of the root and always to exact measurements."

Weaver's work has provided much valuable information on root systems, most of which will probably never be obtainable

again. However the method provides no direct information on the 'preforming capacity' of the root system at any depth.

In Saskatchewan, Pavlychencho (1937) introduced the soil-block washing method. His method involved excavating blocks up to 40 inches by 40 inches by 70 inches, encasing them, removing them from the ground, soaking the entire block and then washing away all the soil. After this, the roots could be studied in detail. This method, as with Weaver's, has provided much valuable information on the form and extent of root systems, as well as data on the effect of competition. However the use of data from these studies to infer preforming capacity at any depth is not valid and may lead to erroneous conclusions concerning the importance of subsoil nutrients (Barley, 1970). Other workers have used a variation of the soil-block washing technique to derive information on root systems. They have taken several core samples around a plant and sectioned them by depth. The soil was then washed away and the roots weighed and/or measured (Mengel and Barber, 1974, Osman, 1971 and Welbank et al.,1974). This method has advantages because it is less plot-destructive and a great deal less tedious than root excavation studies; however a large number of cores must be taken to give representative information on root distribution. Kirby and Rackham (1971) found that root growth of barley appeared to be mainly vertical and stated that roots tend to exploit vertical channels. If this is the case there would be a large amount of variation between

cores. Welbank and Williams (1968) stated that between core variation for the 15 -60 cm depth ranged from 31 to 99 % of the mean. Another problem is that it is difficult to distinquish dead roots from active roots (Cole et al., 1977 and Halm et al., 1971). This may lead to an over-estimation of the quantity of roots, especially in the subsoil, where decomposition of roots may take several years. Another limitation of the method is that it is only useful for determining vertical distribution of plant roots. Most crops are normally grown in a high population density and it is impossible to tell which roots in a core come from a specific plant. Radial distribution can be determined if a plant is grown in isolation, but under such conditions the root distribution will not be indicative of a plant growing in competition with other plants. Pavlychenko (1934) found that an isolated mature plant of rye, wheat or wild oats produced 65 to 80 kilometers of roots, but when grown in drill rows 15 cm apart with 18 to 20 plants every 30 cm produced only about 800 meters of roots.

In an effort to overcome some of the disavantages of the more classical methods of root investigation , the $^{32}P$ plant injection method was developed (Racz et al., 1964 and Rennie and Halstead, 1965). In this method of study a quantity of $^{32}P$ is injected into the stem of a single plant and allowed to equilibrate throughout the plant. Soil cores are taken at various distances from the plant and sectioned by depth. The radioactivity within each core is assumed to

be proportional to the biological activity of roots within that core. There is no problem in differentiating between roots of the plant under study and roots of surrounding plants or dead roots. In this manner it is possible to obtain a measurement of root distribution both radially and vertically. However the method is subject to variability in the same manner as the simple soil core washing method previously described (Kamath and Subbiah,1971, Cholick et al.,1977). This variability may become excessive in soils where root distribution is controlled by soil structure. Another weakness of the method is that the $^{32}P$ tends to concentrate in the areas of maximum biological activity during the period of equilibration. This may result in erroneous conclusions concerning root distribution and the importance of roots in any volume of the rooting zone.

Several different approaches have been employed to obtain information on the ability of roots to absorb nutrients at different depths in the soil. Wiersum (1967) channelled the root systems of plants to various depths in the soil through low nutrient media within tubes. While this method supplies information on the absorbing ability of roots at various depths under different conditions, it ignores the problems roots may encounter in reaching a given depth under normal conditions. As well, it is not possible to determine if growth conditions in one part of the profile alter the amount or activity of roots in another part of the profile.

Bole (1977) developed a method to determine root activity at various depths which overcomes many of the problems encountered with other approaches. The method involves carefully excavating a root and then encasing it in a split plastic tube with soil containing a standard amount of $^{32}P$ labelled phosphorus. After a few days $^{32}P$ activity is determined in the above ground portion of the plant and the absorbing activity of the root is calculated. The advantages of this approach are that roots are grown under normal conditions and nutrient absorption ability is measured under standard conditions. The main disadvantage of the method is numerous measurements must be made in order to obtain the absorption ability of various types of roots of differing ages. As well, the method would be difficult to apply under field conditions.

A method that overcomes many of the problems inherent in the methods described previously is the $^{32}P$ "soil injection" method. This method was introduced by Nye and Foster (1961), although variations of the method had been previously in use. The design intergrates root distribution and root activity. The use of radioactive tracers to measure nutrient uptake from soils depends on the principle of isotope dilution. In general it can be expressed as:

$$Tp/Np = Ts/Ns \quad \text{or} \quad Np = (Tp \cdot Ns)/Ts \qquad (1)$$

where Tp and Np are quantities of tracer and nutrient

absorbed by the plant while Ts is the quanity of tracer added to the soil and Ns is the quantity of nutrient in the soil that equilibrates with the added tracer (Newbould and Taylor, 1964). The isotope dilution principle can be used to determine relative uptake from different compartments of the plant's root zone using the equation:

$$Npi/\sum_{i=1}^{n}Np = (Tpi \cdot Nsi)/\sum_{i=1}^{n}(Tp \cdot Ns) \qquad (2)$$

where n= the number of compartments in the root zone. In crder for equation 2 to provide a valid measure of relative uptake, several criteria must be satisfied. The two most important criteria, as summarized by Newbould and Taylor (1964), are:

1. "the pattern of injections must be uniform in all zones, i.e. the number of injections, the activity of tracer and the geometric pattern must be constant."
2. "within each zone the pattern of absorption by roots must be random relative to the sites of injection."

The first requirement can be met by using a template to control the pattern of injection. The second requirement may cause some difficulties in field crops where planting is not random. This error is decreased by insuring that the injection pattern has a constant spatial relationship with the plants to be sampled for uptake measurements. The injection procedure itself may prevent rooting pattern from being completely random if the injection access holes offer

a more easily penetratable medium than does surrounding soil. Prevention of this possibility can be accomplished by not allowing the roots to use the access holes. This has been accomplished by leaving the access tubes in the access holes after injection (Chan, 1975). A further requirement is that addition of the tracer to the soil must not alter the normal growth habits of the plants under study. Several workers have overlooked this criterion and used $^{31}P$ as a carrier for $^{32}P$ (Nye and Foster, 1961; Murdock and Englebert, 1958 and Lipps et al. 1956). This practice may result in abnormal root proliferation in the volume occupied by tracer. Enhanced root development has been shown to occur in the vicinity of nitrogen and phosphorus bands (Duncan and Ohlrogge, 1958 and Miller and Ohlrogge, 1958). Enhanced root growth in the labelled area can be avoided by using carrier-free $^{32}P$ (Chan, 1975 and Newbould et al. 1971).

However in spite of weaknesses mentioned, this approach does supply information on the ability of a plant to absorb phosphorus in a given compartment if phosphorus is present. Variations of this approach have been used to study the efficiency of plant uptake of fertilizer phosphorus placed in the subsoil (Chan, 1975; Farley, 1973 and Karblane, 1971).

One further requirement must be satisfied before the soil injection method can be used effectively. In soils where phosphorus varies with depth in form and/or amount it is imperative to obtain measurements of the labile

phosphorus at the point of injection (Nye and Tinker, 1977). After injection into the soil $^{32}P$ equilibrates with labile phosphorus present at that point and the specific activity of phosphorus which the roots absorb is inversely related to the size of the labile phosphorus pool. Previously, workers have used greenhouse-determined 'A' values (Nye and Foster, 1961 and Osman, 1971) or laboratory-determined 'E' values (Chan, 1975 and Nye and Foster, 1961) as a measurement of labile phosphorus. Although 'A' values are probably the best method of determining the expected level of isotope dilution, 'A' value determinations are extremely time consuming. Where large numbers of samples must be evaluated, the logistics become insurmountable. 'E' values are more appropriate in many experiments; however problems exist with their use. Russell et al. (1957) stated:

> "When used to assess phosphate status of agricultural soils, tracer methods appear to be subject to limitations similar to those of the older extraction methods."

'E' values are somewhat empirical as different methods may give different results. In a case where two samples differ in chemical characteristics, it is quite conceivable that they contain relatively different proportions of phosphate compounds of differing solubility. Under these circumstances the time required to reach isotopic equilibrium may differ dramatically. Several other factors such as the presence of organic ions, exchangeable base status and temperature have

been shown to affect exchange reactions (Ambarri and Talibudeen, 1959, a, b, c ). However standardized methods have given results which correlate well with phosphorus absorption by plants (Olsen et al. 1954 and Omanwar, 1970). As well, it has been shown that 'E' and 'A' values are highly correlated with those obtained by conventional extraction methods (Olsen et al. 1954 ; Omanwar, 1970 and Omanwar and Robertson, 1973). Osman (1971) conducted a study where large numbers of labile phosphorus measurements were required. To overcome logistical problems he measured labile P using a $CO_2$ extraction and converted the measurements to 'L' values using a linear regression of 'L' value on the $CO_2$ extraction values. In his work he was calculating absolute uptake. If, however, the data generated are relative uptakes, there is no need to make the conversion. To completely justify this approach, the samples studied should have essentially the same chemistry and the regression line should intersect the origin.

As the literature testifies, the methods used to study plant roots differ greatly in both approach and the information obtained. I now propose to review data obtained by the previously discussed methods, as well as other information on the factors affecting plant roots. The review will be divided into two sections, the first dealing with nutrient effects and the second dealing with moisture effects.

## 2.3 Nutrient Effects on Plant Roots

As early as 1862 Nobbe reported that plant roots tended to follow nutrient-enriched soil patterns in cylinders. Since Nobbe's time several workers have reported ramification of roots in enriched portions of soil (Duncan and Ohlrogge, 1958, 1959 and Weaver, 1926). Phosphorus has been shown to promote root growth when applied to plants growing under nutrient deficient conditions (Hackett, 1968). These types of results have led to the commonly held belief that phosphorus has an overall favourable effect on root development. Upon closer examination it becomes apparent that one must look beyond localized effects to gain a clear understanding of how a localized increase in nutrients affects root growth. Weaver and Clements (1938) reported that when roots came in contact with soil layers rich in nutrients they branched profusely but failed to penetrate deeply into the soil. May *et al*. (1965) found that nutrient concentrations that were suboptimal for shoot growth and production of root mass, resulted in barley producing the greatest length of roots. Data reported by Drew *et al*. (1973) indicated that application of high rates of nitrate in one compartment brought about a decrease in root growth in low nitrate compartments. Philipson and Coutts (1977) used a split root technique to study the effect of localized nutrient supply on Lodgepole pine. They found enhanced growth in high nutrient zones and depressed growth in the low nutrient zones, which they thought resulted from

competition for a limited supply of assimilates produced in the above-ground portions. However Drew and Saker (1975) reported there was no evidence that extension of barley seminal axes was reduced by high concentrations of phosphorus in one portion of the root zone. Newbould et al. (1971) studied the effect of fertilizer on uptake of phosphorus by ryegrass. Although the fertilizer was spread on the soil surface and did not affect the quantity of labile phosphorus below 2.5 cm, the uptake of phosphorus below 2.5 cm was affected. There was a 10% increase in absorption from 2.5-7.5 cm depth. As well, there was 50% decrease in P uptake from the 7.5-12.5 cm depth and a 10% decrease from the 17.5-22.5 cm depth. They concluded that an increase of nutrient in one zone can modify either the distribution or function of roots in adjacent zones. Welbank et al. (1974) presented data that showed significant effects of fertilizer on root growth of barley. They found that surficial addition of P or K at all levels of nitrogen studied had no significant effect on root growth in the upper 15 cm but resulted in significant decreases in root weight below 15 cm. Simultaneous addition of P and K resulted in a significant increase in root growth in the 0-15 cm depth and a significant decrease in the 15-30 cm depth. Karblane (1971) reported that mixing superphosphate with the surface horizon brought about a decrease in P uptake from lower horizons. Uptake of subsurface phosphorus declined by 24% and 21% for barley and potatoes

respectively. At the same time grain yield for barley increased from 13.9 g to 42.8 g per pot and potato yield increased from 52.2 g to 85.6 g per pot. Although data were not supplied on root distribution the results are probably explained by a decrease in root growth in the subsoil. However the evidence is by no means conclusive. Kamath and Subbiah (1971) studied the positional effect of phosphorus placement on root activity. They concluded that the amount of phosphorus uptake by maize in any particular root zone is not affected by placement of phosphate in other zones. Newbould (1969) found that mixing fertilizer in the upper 13 cm of soil brought about a marked decrease in the absorption of phosphorus by barley from lower depths on one soil and a marked increase on a another soil. It appears that even for one plant species the effect of nutrient can vary in both degree and direction. It seems that *a priori* predictions, concerning the effect of nutrients on plant roots, are at best somewhat limited in usefulness.

## 2.4 Moisture Effects on Root Growth and Function

Although moisture is known to affect phosphorus uptake, it is not always clear whether it is the distribution or activity of the roots that is primarily affected. The mechanisms by which phosphorus comes in contact with the root surface suggest that the effect of moisture on root activity may be the major factor. Omanwar and Robertson (1970) found that mass flow and diffusion accounted for at

least 97% of the phosphorus absorbed by roots. Changes in moisture content of the soil will affect the rate at which these processes can deliver phosphorus to the plant roots. Mass flow depends upon the gradient in total moisture stress, the permeability of the soil and the concentration of the ion in solution; therefore as soil moisture content decreases the mass flow component of phosphorus supply decreases. Diffusion depends upon the nutrient concentration gradient and the effective diffusion coefficient. For phosphorus the concentration gradient does not vary greatly with moisture changes; however the effective diffusion coefficient does change. It decreases with decreasing volumetric moisture, increasing tortuosity and increasing interaction between the ion and the soil matrix (de Jong and Rennie, 1967). Hutcheon and Rennie (1960) reported a highly significant decrease in the availability of soil phosphorus to wheat as moisture stress increased. At the same time the relative availability of the fertilizer phosphorus banded with the seed increased. Their data indicate that the level of moisture in the soil may have profound effects on the relative importance of soil phosphorus at all depths particularly when phosphorus fertilizer has been applied. Reichman and Grunes (1966) found P uptake by barley roots decreased with decreasing water potential. Thourp (1969) reported that phosphorus uptake by tomato roots was highly correlated with moisture level in the soil. Newbould (1969) found that the supply of moisture caused considerable

quantitative variation in the distribution of P absorption by ryegrass. Rates of P absorption were positively correlated with the levels of moisture. His data indicated that the relative importance of P at 45 and 60 cm depth was greater in the treatments that received a limited supply of water. However the absolute uptake from subsoil appeared to be approximately equal for both moisture regimes for the season as a whole. While in general, the effect of moisture on root absorption of phosphorus is understood, the data pertaining to the effect of moisture on root growth and distribution is somewhat ambiguous. Russell (1961) states that if conditions are continually moist all plants are shallow rooted. However Cullen et al. (1972) found that rooting did not remain shallow if the profile is continually moist. Thompson and Burrows (1920) found that lucerne roots penetrated to the full depth wetted by irrigation but did not go past the wet front. Thourp (1969) used a split root technique, in which roots of the same tomato plant were simultaneously placed in compartments of different moisture contents. He found, that within the moisture range he studied (4-22%), root growth occurred mainly in the higher moisture compartment. Rowse (1974) found that when root growth of lettuce is restricted near the surface by lack of moisture, the plants compensate by producing more roots in the deeper soil layers. However, Hurd (1968) reported that the response to varying moisture conditions may be under considerable varietal control. Of seven varieties of spring

wheat he studied under high and low moisture levels only one variety appeared to alter its rooting habit in response to moisture levels by increasing root growth in the higher moisture subsoil. As with nutrient effects, it is difficult to accurately predict the effect of moisture on the distribution of P uptake.

## 2.5 Nutritional Importance of Subsoil Phosphorus

It has been recognized for many years that plant roots may penetrate to considerable depths (Weaver 1926). However, as has been indicated previously, the mere presence of roots in the subsoil does not guarantee that they absorb significant amounts of plant nutrients. Wiersum (1967) and Bole (1977) studied the efficiency of roots deeper in the soil. Wiersum found that wheat, broadbeans and *Brassica* roots are as efficient per unit weight in absorbing phosphorus when growing at 80 cm depth as at shallower depths. Conversely, Bole found that the ability of roots of wheat and rape to absorb P decreased substantially with increasing depth. He reported minimal uptake of phosphorus from depths greater than 30 cm, although rape had 50% of its total root length below 30 cm after 45 days. The contradictory nature of the results reported by Bole and Wiersum indicates that the efficiency of roots in the subsoil may vary greatly with changing conditions. A possible fault in Bole's approach is that he apparently did not study absorption and transport under conditions of P

stress. There is evidence that absorption and transport of phosphorus may be increased dramatically if a phosphorus stress is imposed as would be the case if the surface horizon became dry or were low in available phosphorus (Clarkson et al. 1977, and Drew and Saker, 1978). In Bole's and Wiersum's studies the soils used were uniform with depth and the information obtained concerned the change in efficiency of roots with increasing depth. But of equal importance are changes in soil with depth which may alter the availability of phosphorus to plant roots. This has been examined by growing plants in soil excavated from the depth of interest. Halstead et al. (1957) studied six profiles from eastern Ontario. They found that, in general , topsoil was capable of supplying much more phosphorus than subsoil. However in two of the six profiles studied, plants were able to obtain more phosphorus from the subsoil than from the topsoil. Nye and Foster (1961) used a tracer technique to study the distribution of phosphorus uptake by maize and pigeon peas under field conditions. They found that maize obtained 59% of its phosphorus from depths less than 12.7 cm and 93% from depths less than 25 cm. Pigeon peas obtained 49% of their phosphorus from depths less than 12.7 cm and 89% from depths less than 25 cm. Newbould and Taylor (1964) found that under field conditions phosphorus uptake by lucerne and ryegrass dropped dramatically at depths greater than 20 cm. Newbould (1969) found that barley obtained between 3 and 10 times as much phosphorus from the 5-10 cm

depth as it did from the 25-30 cm depth. Karblane (1971) found that barley obtained up to 89% of its phosphorus from the upper 20 cm.

In general, the literature indicates that 80-90% of the phosphorus taken up by plants is obtained from the upper 20-25 cm. However it must be emphasized that these figures are estimates and are based on very few observations. The literature also indicates that the importance of subsoil phosphorus varies significantly for different plant species, different varieties of the same species and changes in growing conditions. Since knowledge of the role of subsoil phosphorus is important in determining the phosphorus fertility of a soil it seemed desirable to conduct a study to assess the importance of subsoil phosphorus to barley in Alberta.

# 3. Materials and Methods

## 3.1 Field Experiments 1976

The 1976 field experiments were designed to determine the importance to barley nutrition of soil phosphorus at depths greater than 15 cm. Plots were set out at three locations , one to represent each of three soil orders; Chernozemic at Ellerslie, Luvisolic at Breton and Solonetzic at Vegreville. Legal locations and the results of physical and chemical analyses are given in Appendix 1. These sites were chosen as they represented a range of soil properties. This was considered desirable as work reported in the literature indicated that soil properties may have a decided effect on root growth and distribution. It was hoped that the range of properties would provide information on root activity that would be applicable to a wider variety of soils than that commonly found in the literature . The review of literature had indicated that moisture and available phosphorus may have an effect on distribution and biological activity of plant roots. The field experiments, which included two levels of moisture, two levels of phosphorus fertilization and three depths of phosphorus uptake, were laid out in split plot factorial design. The $^{32}P$ uptake plots or 'microplots' were located at the centre of long yield plots (Fig. 1). Prior to seeding the plots at Ellerslie and Breton, they were staked out and nine cores to a depth of 60 cm were taken using a truck mounted hydraulic

corer. Samples from Vegreville were taken from the guard-row area at the time of the first irrigation. The cores were sectioned into 15 cm lengths and bulked with respect to depth. Moisture was determined gravimetrically on all bulk samples, while extractable phosphorus was determined on the three samples from 0-45 cm depth. Prior to seeding, monocalcium phosphate was broadcast at rates of 10 kg P/ha on low phosphorus treatments and 40 kg P/ha on high phosphorus treatments. The plot areas were rotovated twice to incorporate the phosphorus uniformly throughout the top 15 cm of soil and then harrowed twice to ensure a level, firm seedbed. The plots were seeded to barley (cultivar 'Galt') at 110 kg/ha with 18 cm row spacings. The date of seeding for each site is given in Table 1. Concurrent with seeding, 48 kg N/ha was broadcast to the complete plot area using ammonium nitrate at Ellerslie and Vegreville, and an equal mixture of urea and ammonium sulfate at Breton to ensure there was not a sulphur deficiency. After seeding, $^{32}P$ microplots were set up in much the same manner as done by Chan (1975). Plastic tubes with an outside diameter of 13 mm and an inside diameter of 10 mm were slipped over a steel probe and inserted into the soil in a grid pattern. (Fig. 2) A plywood template was used to maintain the same pattern for all microplots. The tubes were inserted to depths of : 10 cm for the 0-15 cm compartments, 22.5 cm for the 15-30 cm compartments and 37.5 cm for the 30-45 cm compartments. After the tubes were set in the soil, 10 uCi of carrier free

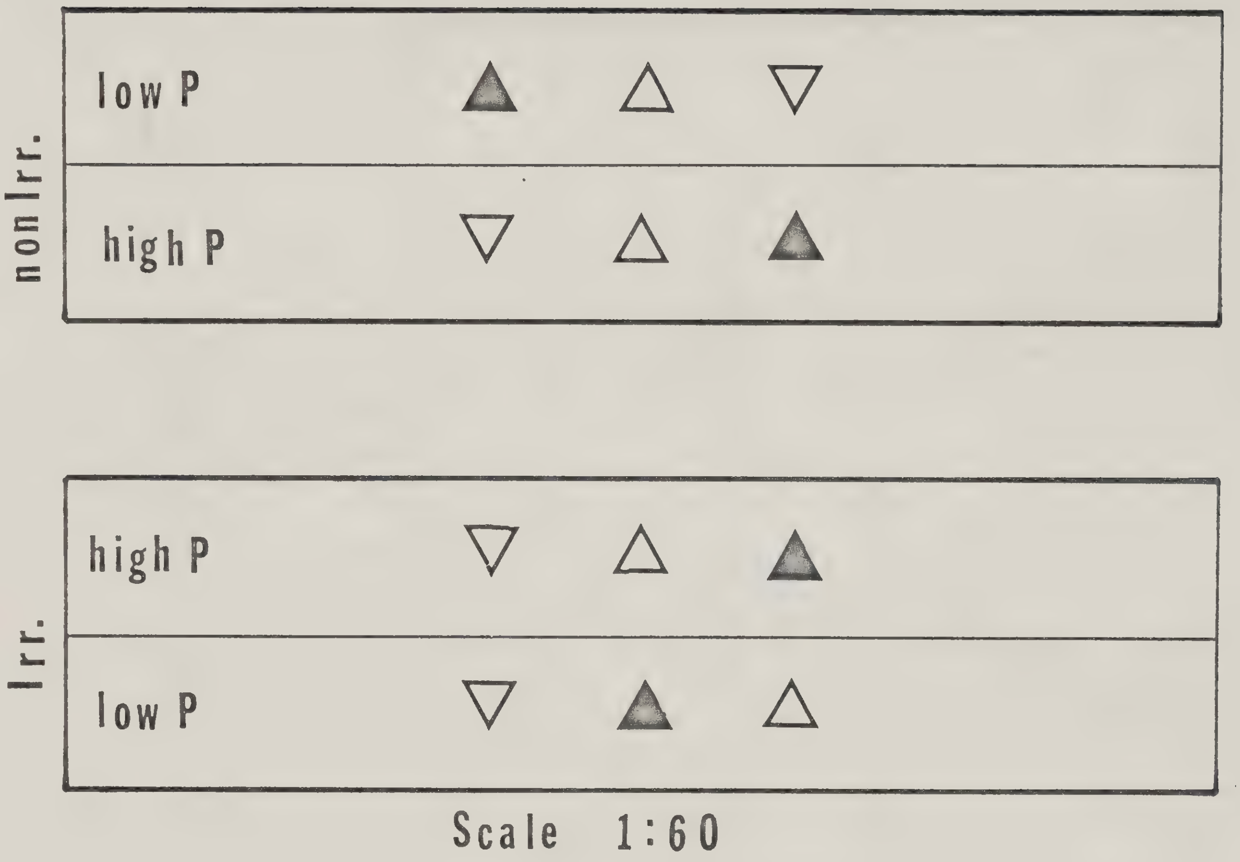



Figure 1 Plane view showing one replicate of a 1976 field plot. Microplot positions are represented by triangles. ( ▲ 0-15 cm depth, △ 15-30 cm depth, ▽ 30-45 cm depth)

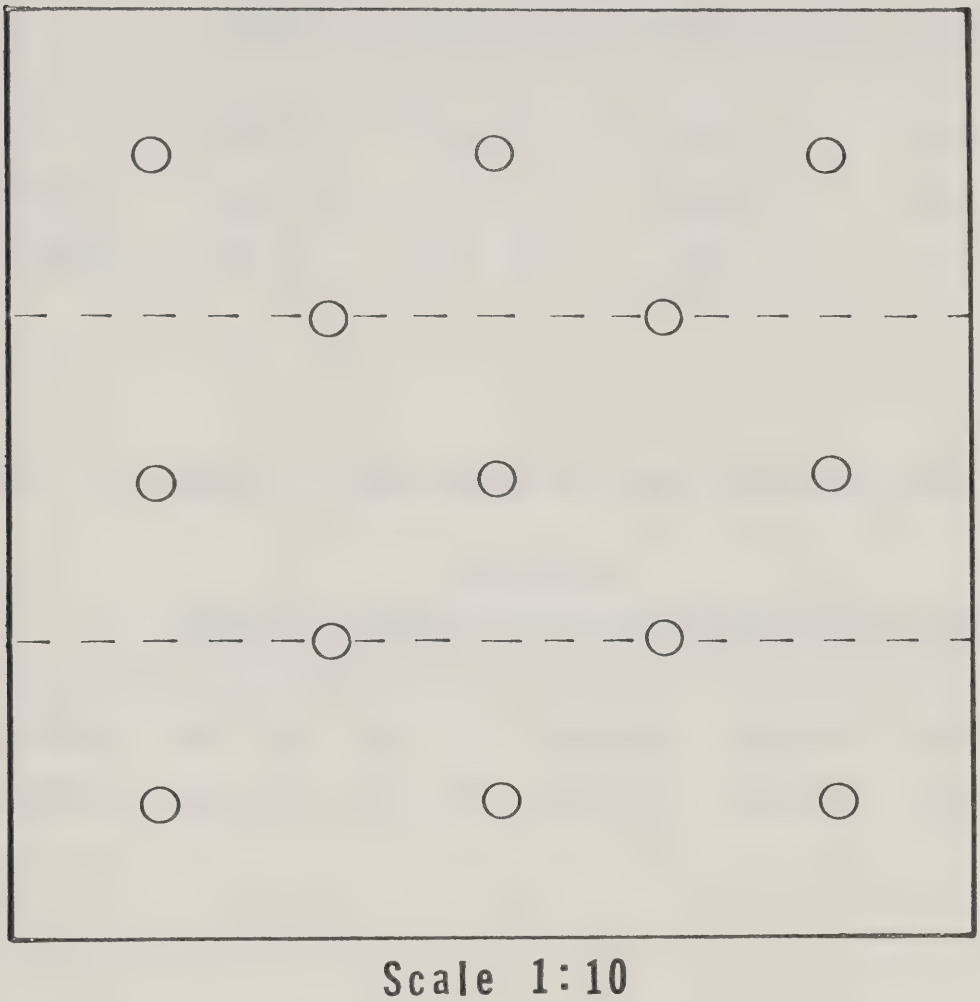



Figure 2 Plane view of grid pattern for $^{32}P$ microplots showing the position of injection tubes (○) and the relationship to the barley seed row (---).

Table 1 Dates of operations for the 1976 field studies.

| Site | Operation | | | |
|---|---|---|---|---|
| | Seeding | Irrigation 1 | Irrigation 2 | Harvest |
| Breton | May 13 | June 10 | July 13 | Sept. 1 |
| Ellerslie | May 21 | June 8 | June 29 | Aug. 21 |
| Vegreville | May 25 | June 17 | July 5 | Aug. 23 |

Table 2 Dates of operations for the 1977 field studies.

| Site | Operation | | | | |
|---|---|---|---|---|---|
| | Seeding | Emergence | Harvest 1 | Harvest 2 | Harvest 3 |
| Ellerslie | May 25 | July 1 | June 22 | July 6 | July 20 |
| Vegreville | June 6 | June 13 | July 11 | July 25 | August 8 |

$^{32}P$ in 10 ml of H2O solution was injected into each of the 13 tubes for a total of 130 uCi per microplot. The tubes were left in place because it was thought this would cause less disturbance of the natural root distribution than would their removal. (Chan,1975 and Paasikallio, 1976). An attempt was made to seal the tubes to prevent entrance of air and water. This was not entirely successful because the plaster used to seal the tubes shrank and left many of the tubes open. At the dates indicated in Table 1, the high moisture treatments received approximately 50 mm of additional water. The water was applied using a truck-mounted tank and pump connected to "soaker" hoses. Prior to irrigation, moisture samples were taken to a depth of 60 cm using an Oakfield core sampler. Approximately three weeks prior to harvest, root distributions were determined by the '$^{32}P$ plant injection method' (Rennie and Paul, 1971).

At maturity, plant samples were taken from yield plots and microplots for each treatment. The samples were dried at 70° C for 48 hours, weighed, ground and analysed for phosphorus. The $^{32}P$ activity of all microplot samples was determined and used to calculate phosphorus uptake from each depth (Appendix 2). Concurrent with harvest, soil cores were taken for determination of moisture, bulk density and extractable phosphorus.

## 3.2 Field Experiments 1977

The 1977 field experiments were altered significantly from the 1976 experiments. The experiments were designed to evaluate uptake of phosphorus from the upper 45 cm of soil in relation to time and soil moisture. The time variable was included because several workers have shown rather significant amounts of senecence of roots during the season, particularly in the upper 15-20 cm of soil (Mengel and Barber, 1974; Osman, 1971 and Welbank *et al*. 1974). It was thought that a single root measurement at the end of the season, as was done during the first year, may lead to an erroneous conclusion concerning the number and efficiency of roots at any particular depth.

Initially three sites were chosen adjacent to the 1976 sites; however the Breton site was later abandoned because of poor seedling emergence. Soil chemical and physical properties for the experimental sites are given in Appendix 1. The experimental design chosen was a split-plot factorial with three replicates where the measured parameter was phosphorus uptake and the independent variables were time of sampling and depth in the soil. The design included three harvest dates for each depth, with the exception of the 30-45 cm compartment at the first harvest.

After staking out the sites, but prior to fertilization, each yield plot was sampled to a depth of 90 cm with one core taken beyond each end of the microplot area. The cores from each yield plot were sectioned into 15

cm lengths and bulked with respect to depth. Moisture contents were determined for all samples while extractable phosphorus contents and pH (1:2.5) were determined for the samples from the 0-45 cm depth. The entire experimental area was fertilized with 56 kg P/ha as calcium monophosphate which was incorporated using a rotovator at Ellerslie and a double-disc and rotovator at Vegreville. After incorporation the plot areas were double harrowed to ensure a firm, level seedbed. After an equilibration period of seven days, surface soil samples were taken and sites were seeded to barley (cultivar 'Galt') at 112 kg/ha with a blanket application of 48 kg N/ha as ammonium nitrate. The microplots were set up in the same manner as in the 1976 field experiments. Harvests were carried out at 21, 42, and 56 days after emergence at Ellerslie and 28, 42 and 56 days after emergence at Vegreville (Table 2). At each harvest, plant samples were taken from yield plots for determination of the total P in the above ground portion and from the micro plots for determination of uptake with respect to depth. The $^{32}P$ specific activity of all microplot samples was determined and used to calculate phosphorus uptake from each depth (Appendix 2). At each harvest soil samples were taken from 0-15 cm on all plots and from 0-90 cm on harvested plots. Moisture and extractable phosphorus were determined for samples to a depth of 45 cm and moisture only for samples from 45-90 cm depth. At each harvest root distribution was determined by $^{32}P$ plant injection method

(Rennie and Paul, 1971).

### 3.3 Greenhouse Experiment

The greenhouse experiment, using bulk samples from the 1976 field experiments, was conducted to determine the availability to barley of soil phosphorus at different depths in the profile. Soil from 0-15 cm, 15-30 cm and 30-45 cm for each site was collected, air dried and passed through a 6 mm sieve. Washed sand was then mixed with the soil in a 3:8 ratio in order that potential structural problems be avoided. The study involved two treatments, one where no phosphorus was added and a second where phosphorus was added to give an initial soil solution concentration of 0.3 ug P/ml as determined from phosphorus sorption isotherms. P sorption data is given in Appendix 4. It was thought the soil solution phosphorus concentration would remain above 0.2 ug P/ml for the duration of the study. It has been suggested that 0.2 ug P/ml is sufficient to ensure there is not a phosphorus deficiency (Beckwith, 1964 and Fox and Kamprath, 1970). All soils received a blanket treatment of 50 ug N, 125 ug K and 5 ug S per gram of soil, as well as, micro nutrients (Khan, 1967). Three weeks after emergence an additional 40 ug N/g and 4 ug S/g was applied to all pots. The soil-sand mixtures were placed in pots, brought to field capacity and allowed to equilibrate for a few days. Each pot was seeded with 12 barley seeds (cultivar 'Galt') and thinned to 6 healthy plants after emergence. Room

temperature was maintained at a minimum of 15° C and plants received artificial light for 17 hours per day. At 43 days after seeding, the above ground portions of the barley plants were harvested, dried at 70° C for 48 hours, weighed and analyzed for total phosphorus. Extractable phosphorus was determined on soil samples before addition of phosphorus and after harvest.

## 3.4 Analytical Methods

### 3.4.1 Soil Physical Analyses

Physical analyses were done on composite samples from each site which were air dried and ground to 2 mm using a flail grinder. Particle-size analysis was done by the hydrometer procedure (McKeague, 1978). Moisture content at -1/3 bar was determined using the pressure plate extraction method and at -15 bar using the pressure membrane extraction method (McKeague, 1978). Bulk density was determined on cores taken with a truck-mounted hydraulic corer as outlined in McKeague (1978).

### 3.4.2 Soil Chemical Analyses

#### 3.4.2.1 Site Characterization

Soil reaction was determined on composite samples using the saturated paste method and electrical conductivity was determined on saturation extracts of the same samples (McKeague, 1978). Sodium adsorption ratio was determined using saturation extracts (McKeague, 1978). Total carbon was

done by dry combustion using a Leco induction furnace (McKeague, 1978). $CaCO_3$ equivalent was determined using the calcimeter method (Bascomb, 1961).

### 3.4.2.2 Soil Phosphorus Analysis

Extractable phosphorus was determined by the Miller and Axley, and Olsen methods as described by Alexander *et al.* (1972). Phosphorus sorption isotherms were determined using the method outlined by Robertson and Bache (1978). Air dried soil samples weighing 2.5 g were added to a series of water solutions of known phosphorus concentration. The mixtures were shaken for 18 hours and then filtered. The filtrate was centrifuged and an aliquot removed for phosphorus determination. Sorption curves were plotted and phosphorus requirement to bring the soil solution concentration to 0.3 ug P/ml was determined. All phosphorus determinations on soil extracts were done by the ascorbic acid method (Alexander *et al.*, 1972).

### 3.4.3 Plant Analysis

All plant samples were dried at 70° C for 48 hours, weighed, ground and analyzed for phosphorus content. Plant material for total phosphorus determination for the 1976 field trials and the greenhouse study was digested by a wet ashing technique using $HNO_3$, $H_2SO_4$ and a small amount of $HClO_4$ (Rennie and Paul, 1971). Phosphorus concentration of plant digests from 1976 field studies and greenhouse study

were determined using the ascorbic acid method (Alexander *et al.* 1972). Plant material for total phosphorus determination for 1977 samples was digested by a dry-ashing technique using $Mg(NO_3)_2$ and MgO (Horwitz, 1975). Determination of phosphorus concentrations in the digests were done by the vanadate-molybdate-yellow method.

### 3.4.4 Isotope Methods

#### 3.4.4.1 32P Activity in Plant Material

One ml aliquots of the aqueous digests from total plant analyses were transferred using an Oxford pipette with disposible tips to 20 ml glass scintillation vials containing 10 ml of Scintiverse scintillant. The mixtures were shaken and then counted using a scintillation counter with programable channel settings (Isocap 300 manufactured by Searle Analytical). Counting times were normally set to a maximum of 20 minutes as the large number of samples and short halflife of $^{32}P$ resulted in time constraints. All counts were corrected for background and isotopic decay. Quench corrections were done when necessary; however this was not normally required as usually there were no significant differences between samples in counting efficiency, and the ultimate use of the data only required that the counts have the same relative efficiency.

#### 3.4.4.2 Exchangeable Phosphorus

Exchangeable phosphorus was determined by two methods.

Method A was based on a modification of that outlined by Omanwar (1973). Soil samples of 1.25 g were equilibrated with 25 ml of 0.01 M $CaCl_2$ solution for a period of 24 hours in 50 ml polycarbonate centrifuge tubes. After equilibration 0.2 ml of solution containing a known amount of $^{32}P$ was added to the sample and shaken for a period of one hour. The samples were then centrifuged at 27,000 G for 10 minutes. The supernatant was filtered through Whatman 42 filter paper. Aliquots of the filtrate were taken using an Oxford pipette with disposible tips for determination of $^{32}P$ activity and phosphorus concentration. Calculation of 'E' value was determined using the equation:

$$E = {}^{31}P(\text{solution}) \cdot Ci \; / \; (Cf \cdot W) \qquad (3)$$

where Ci and Cf are the initial and final $^{32}P$ activity in solution and W is the sample weight. Method A proved unsuitable for the subsoil samples because the $Ca^{++}$ ion depressed P solubility which made accurate determinations of phosphorus concentration impossible. A second method, method B, was designed primarily to study 'E' values in the subsoil. In order to obtain reliable results several modifications in the method were made. The 0.01 M $CaCl_2$ solution was replaced with deionized water, the $^{32}P$ equilibration period was increased to four hours and the soil-solution ratio was decreased from 1:20 to 1:10. The combination of changes resulted in less variability in

results; however there were problems with highly coloured solutions.

# 4. Results and Discussion

## 4.1 Field Experiments 1976

### 4.1.1 Effects of Irrigation and Phosphorus Fertilizer on Yield and Phosphorus Uptake by Barley

As stated previously the primary purpose of the 1976 study was to obtain data on the importance to barley nutrition of subsoil phosphorus. In order to increase the scope of the study, irrigation and fertilizer phosphorus treatments previously described were included. As has been discussed rainfall and fertilizer practice are among the more variable factors that are likely to affect crop growth and nutrient uptake.

#### 4.1.1.1 Irrigation

Although irrigation is not normally required in central Alberta, spring rains had been sparce and soil moisture content was low at all sites (Table 3). If conditions prevailing at seeding had continued, the effect of moisture may have been more evident. However, rainfall during the growing season was abundant with 340 mm, 210 mm and 220 mm at Breton, Ellerslie and Vegreville respectively. All sites received a relatively high proportion of their rainfall during the early part of the growing season when extra water was being applied to the irrigation treatments(Fig. 3). Moisture samples taken prior to the second irrigation showed no observable effects of irrigation on soil moisture status

(not shown in data). Irrigation resulted in no significant changes in total phosphorus uptake at the three sites (Table 4). The Breton site showed no significant changes in either grain yield or phosphorus content in the grain. The response to irrigation at the Ellerslie and Vegreville sites was different from that at the Breton site. The barley at both sites showed trends for decreases in grain yield on the irrigated treatment and increases in phosphorus content of the grain. However the only significant effect ($P \leq 0.05$) was the change in phosphorus content at the Ellerslie site. The reason the barley at the Ellerslie site showed a response to irrigation is not clear. Both irrigations at all sites were carried out during the first six weeks of the growing season (Table 1). All sites probably received sufficient moisture from rainfall during this period to preclude the need for additional moisture (Fig. 3). The reason may be that the Vegreville and Ellerslie sites received more rainfall and had higher soil moisture contents than the Breton site (Table 3). It is possible that increased moisture may have resulted in an increase in phosphorus diffusion coefficients which would tend to increase phosphorus uptake while at the same time having negative effects on crop growth because of impaired aeration.

### 4.1.1.2 Phosphorus Fertilizer

Barley showed an increase in total phosphorus uptake when P fertilizer was increased from 10 to 40 kg/ha (Table

Table 3 Soil moistures (%) for 1976 field studies.

| Site | Depth cm | Time of Sampling Seeding | Irrigation 1 | Irrigation 2 | Harvest |
|---|---|---|---|---|---|
| Breton | 0-15 | 16 | 16 | 19 | 24 |
| | 15-30 | 19 | 18 | 19 | 21 |
| | 30-45 | 20 | 20 | 19 | 21 |
| | 45-60 | 19 | 20 | 19 | 22 |
| Ellerslie | 0-15 | 25 | 23 | 32 | 36 |
| | 15-30 | 19 | 22 | 27 | 28 |
| | 30-45 | 16 | 16 | 23 | 17 |
| | 45-60 | 17 | 18 | 19 | 14 |
| Vegreville | 0-15 | * | 26 | 23 | 20 |
| | 15-30 | * | 22 | 20 | 13 |
| | 30-45 | * | 21 | 21 | 12 |
| | 45-60 | * | 19 | 18 | 13 |

* Moisture samples not taken.

Table 4 Phosphorus uptake, yield and P content of barley for 1976 field studies.

| Site | Fertilizer Treatment | | Moisture Treatment | |
|---|---|---|---|---|
| | (10 kg P/ha) | (40 kg P/ha) | Natural | Irrigated |
| (a) Phosphorus uptake (kg P/ha) | | | | |
| Breton | 10.1 | 11.7* | 10.8 | 11.0 |
| Ellerslie | 11.3 | 13.1 | 12.2 | 12.5 |
| Vegreville | 8.2 | 11.8* | 10.0 | 10.0 |
| (b) Barley yield (tonne/ha) | | | | |
| Breton | 2.70 | 3.11* | 2.88 | 2.92 |
| Ellerslie | 3.05 | 3.37 | 3.39 | 3.04 |
| Vegreville | 2.74 | 3.68 | 3.31 | 3.10 |
| (c) Phosphorus % in barley grain | | | | |
| Breton | 0.38 | 0.38 | 0.38 | 0.38 |
| Ellerslie | 0.37 | 0.40* | 0.36 | 0.41* |
| Vegreville | 0.30 | 0.32 | 0.30 | 0.32 |

* Treatment level effect significant at P=0.05.

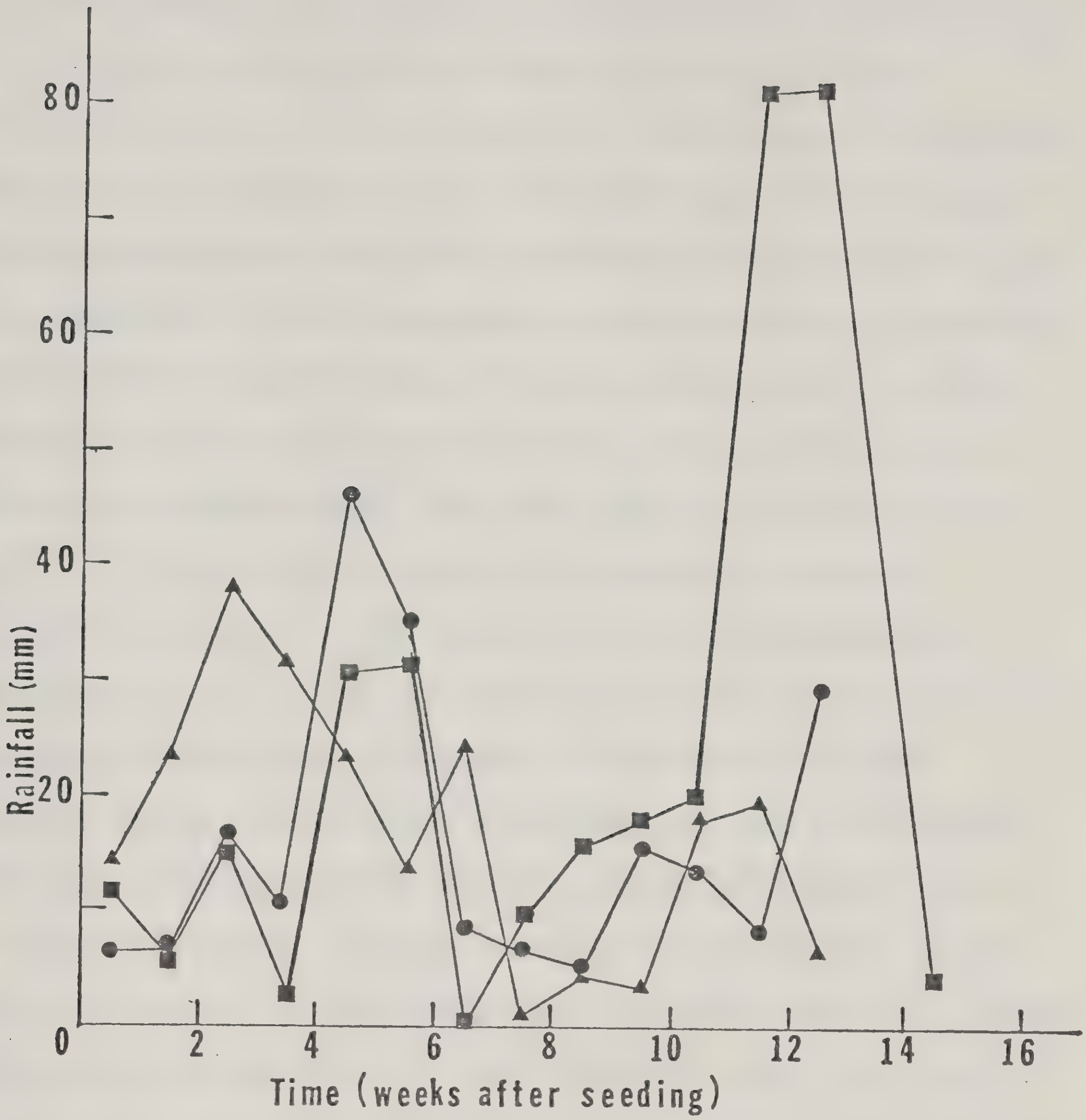



Figure 3 Rainfall patterns during the 1976 field studies at Breton ( ■ ), Ellerslie ( ● ) and Vegreville ( ▲ ).

4) at all sites. The increase was significant ($P \leq 0.05$) only at the Breton and Vegreville sites. Plot variability probably accounted for the lack of a significant fertilizer effect at the Ellerslie site. The additional 30 kg P/ha on the high phosphorus treatment resulted in 16, 19 and 43 per cent increases in the phosphorus uptake at Breton, Ellerslie and Vegreville respectively. The high phosphorus treatment resulted in increased yields at all sites, although the increase was significant ($P \leq 0.05$) only at the Breton site. As well, Ellerslie and Vegreville showed increases in phosphorus content of the grain however the increase was significant only at the Ellerslie site. The reasons for the relatively large yield response at Vegreville are not entirely clear. Extractable phosphorus by the Olsen method indicates that Vegreville had the lowest phosphorus status of the three sites; however, extractable phosphorus by the Miller and Axley method indicates Vegreville site has higher extractable phosphorus than the Ellerslie site (Table 5). It appears that the amount of extractable phosphorus in the top 15 cm of soil, as measured by the two methods in use in western Canada, fails to adequately predict phosphorus availability to barley. The Vegreville site also had a significant fertilizer-irrigation interaction, with irrigation resulting in an 8% increase in uptake of phosphorus on the low level phosphorus treatment and a 6% decrease on the high phosphorus treatments. Duncan's multiple range test revealed that these changes were

Table 5 Summary of extractable phosphorus for 1976 field studies.

| | | Miller and Axley Extraction | | Olsen Extraction | |
|---|---|---|---|---|---|
| | Depth | Treatment | | Treatment | |
| Site | cm | HP * | LP | HP | LP |
| Breton | 0-15 | 19 | 14 | 17 | 13 |
| | 15-30 | 3.4 | 3.4 | 2.6 | 2.6 |
| | 30-45 | 4 | 4 | 3.5 | 3.5 |
| Ellerslie | 0-15 | 14 | 11 | 13 | 10 |
| | 15-30 | 3.9 | 3.9 | 2.3 | 2.3 |
| | 30-45 | 2.5 | 2.5 | 1.8 | 1.8 |
| Vegreville | 0-15 | 17 | 14 | 12 | 8 |
| | 15-30 | 2.4 | 2.4 | 1.9 | 1.9 |
| | 30-45 | 1.9 | 1.9 | 2.4 | 2.4 |

* HP = (40 kg P/ha)
LP = (10 kg P/ha)

significant ($P \leq 0.05$). The low phosphorus treatment was phosphorus deficient and it is possible that the increase in moisture resulting from irrigation may have increased the phosphorus diffusion coefficient. The benefits of increased phosphorus availability because of increased diffusion would not have been as important on the high phosphorus treatment. The adverse effects of high soil moisture levels may have more than outweighed the benefits of increased phosphorus availability on the high phosphorus treatments.

### 4.1.2 Effects of Irrigation and Phosphorus Fertilizer on Uptake of Phosphorus from Lower Depths

#### 4.1.2.1 Irrigation

Statistical analyses of P uptake showed no significant effect of irrigation on phosphorus uptake from lower soil layers. However the extreme variability of uptake measurements may have hidden actual effects and the following trends were noted. Irrigation treatments at Ellerslie and Breton showed apparent increases of 25% and 40% uptake from lower depths while Vegreville had a 33% decrease (Fig. 4-9). If one assumes that increased uptake from depth on a given soil would result from a combination of more favourable moisture conditions and increased root activity at a given depth an interpretation of the trends is possible. At the Vegreville site it is probable that increased moisture resulted in swelling of the Bnt horizon. This would interfere with the movement of roots and oxygen

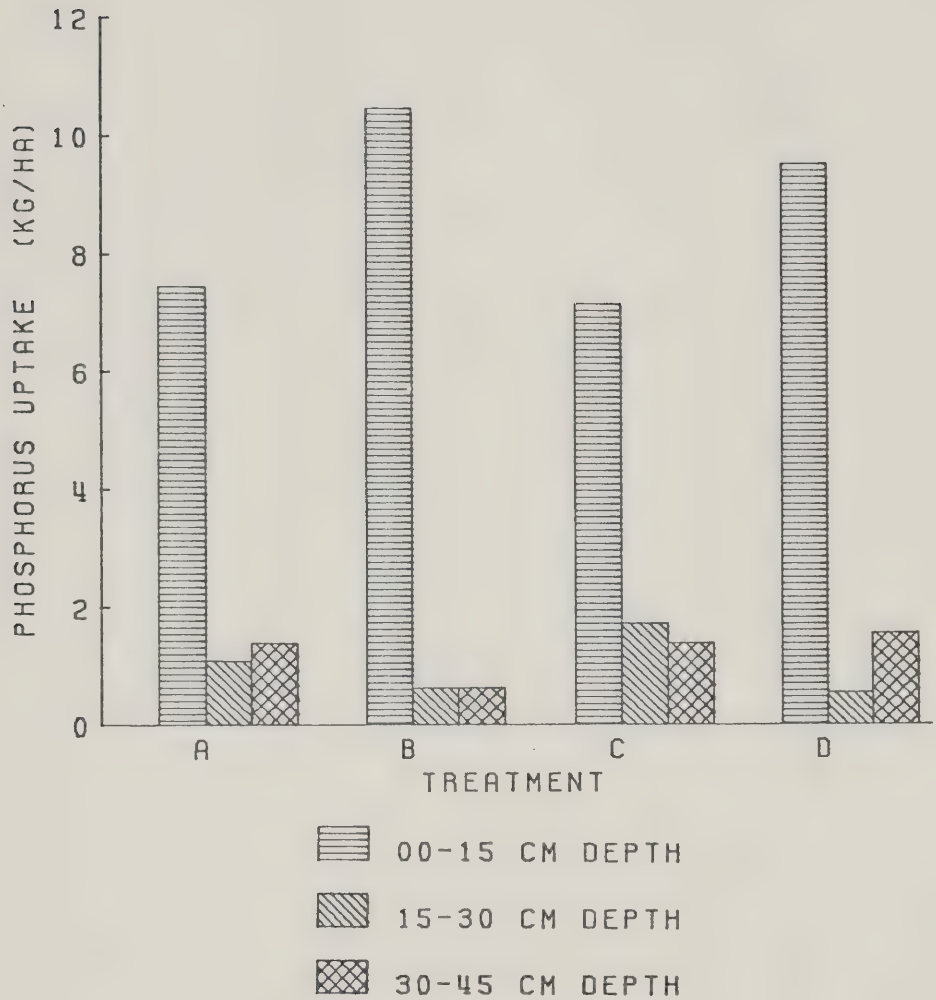



Figure 4 P uptake from three depths by barley for the 1976 Breton site using the Olsen method to estimate exchangeable P. The four treatments are: A non-irrigated, 10 kg P/ha; B non-irrigated, 40 kg P/ha; C irrigated, 10 kg P/ha; D irrigated, 40 kg P/ha.

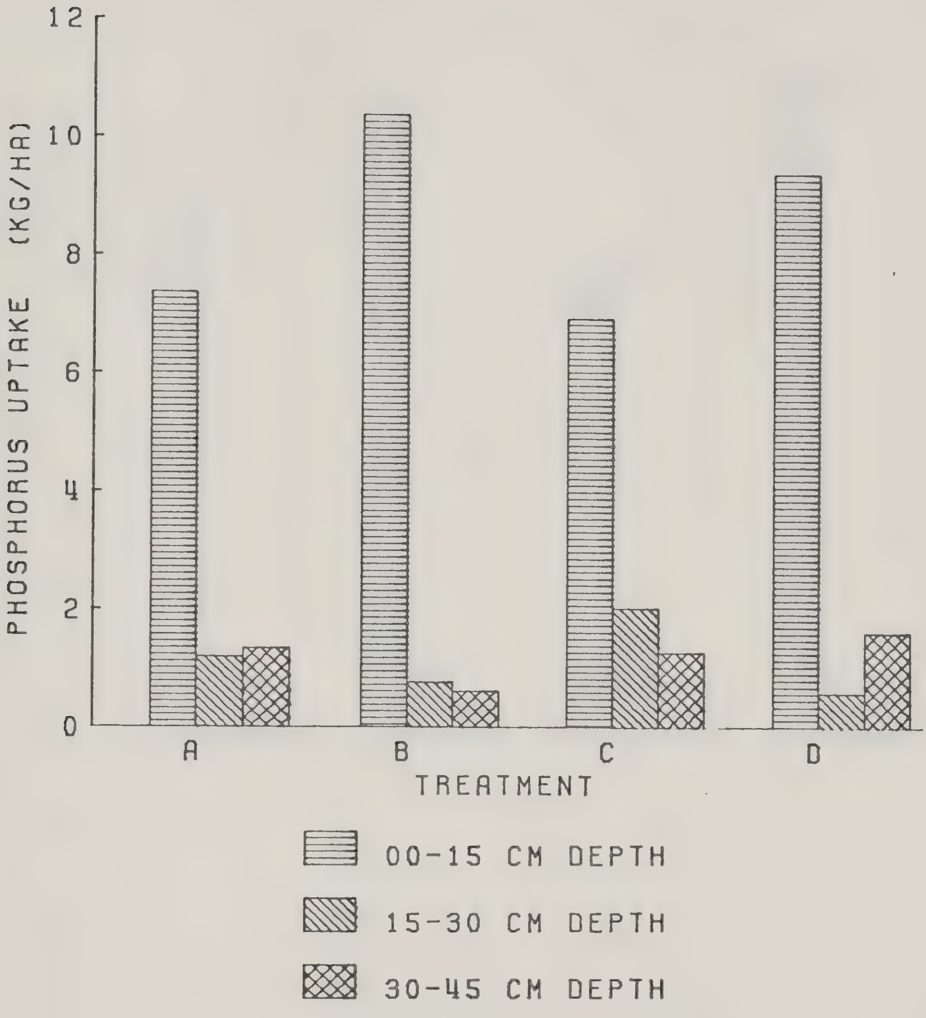



Figure 5 P uptake from three depths by barley for the 1976 Breton site using the Miller and Axley method to estimate exchangeable P. The four treatments are: A non-irrigated, 10 kg P/ha; B non-irrigated, 40 kg P/ha; C irrigated, 10 kg P/ha; D irrigated, 40 kg P/ha.

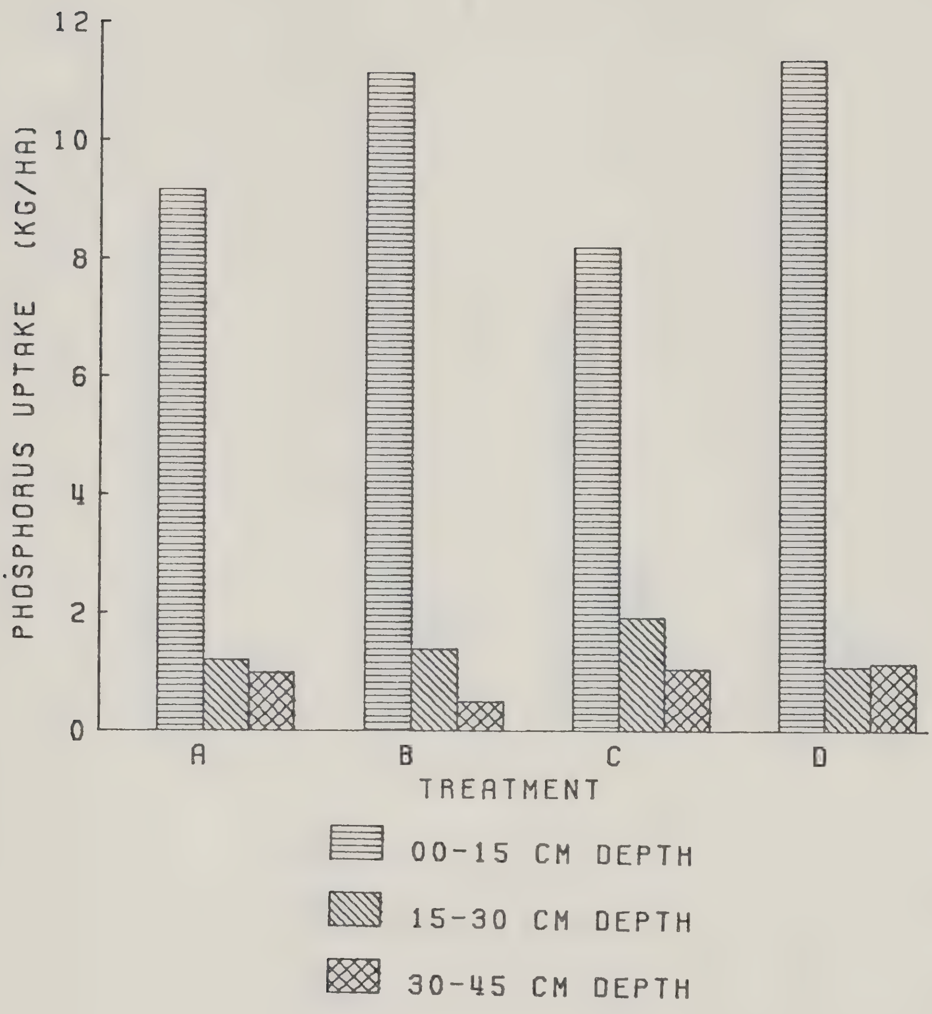



Figure 6 P uptake from three depths by barley for the 1976 Ellerslie site using the Olsen method to estimate exchangeable P. The four treatments are: A non-irrigated, 10 kg P/ha; B non-irrigated, 40 kg P/ha; C irrigated, 10 kg P/ha; D irrigated, 40 kg P/ha.

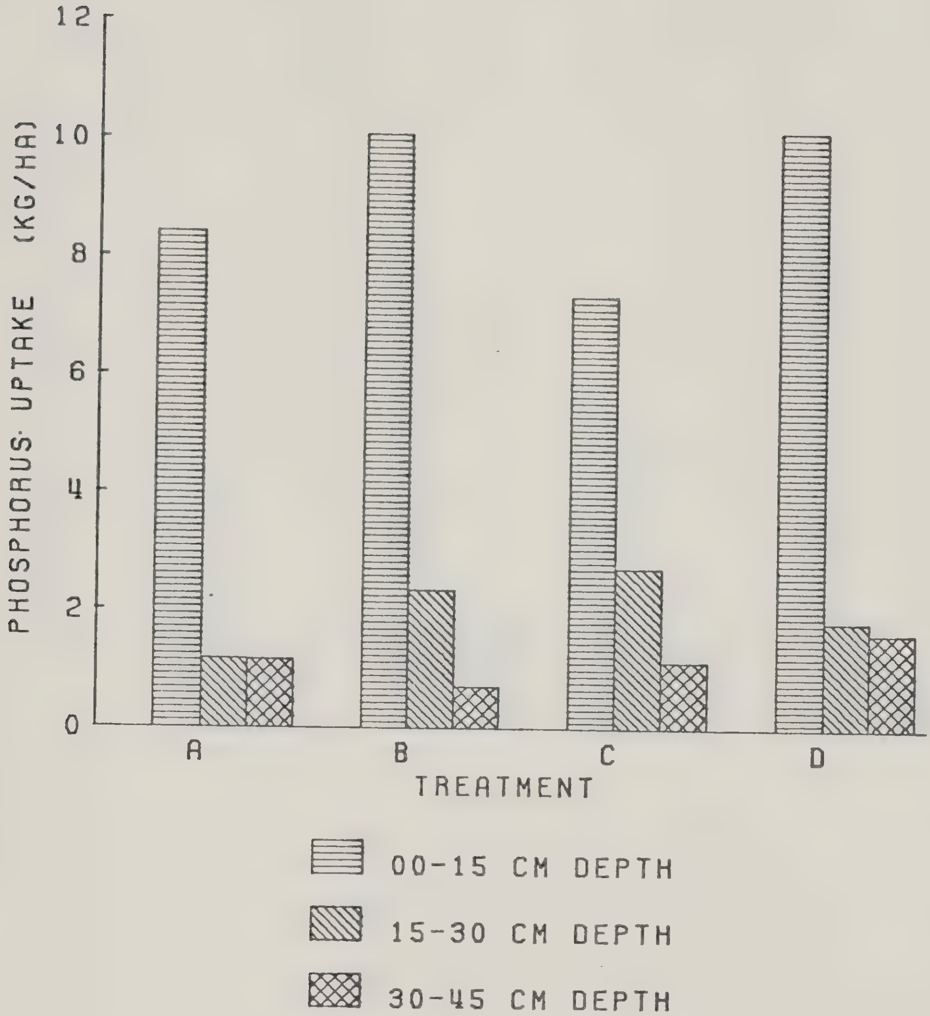



Figure 7 P uptake from three depths by barley for the 1976 Ellerslie site using the Miller and Axley method to estimate exchangeable P. The four treatments are: A non-irrigated, 10 kg P/ha; B non-irrigated, 40 kg P/ha; C irrigated, 10 kg P/ha; D irrigated, 40 kg P/ha.

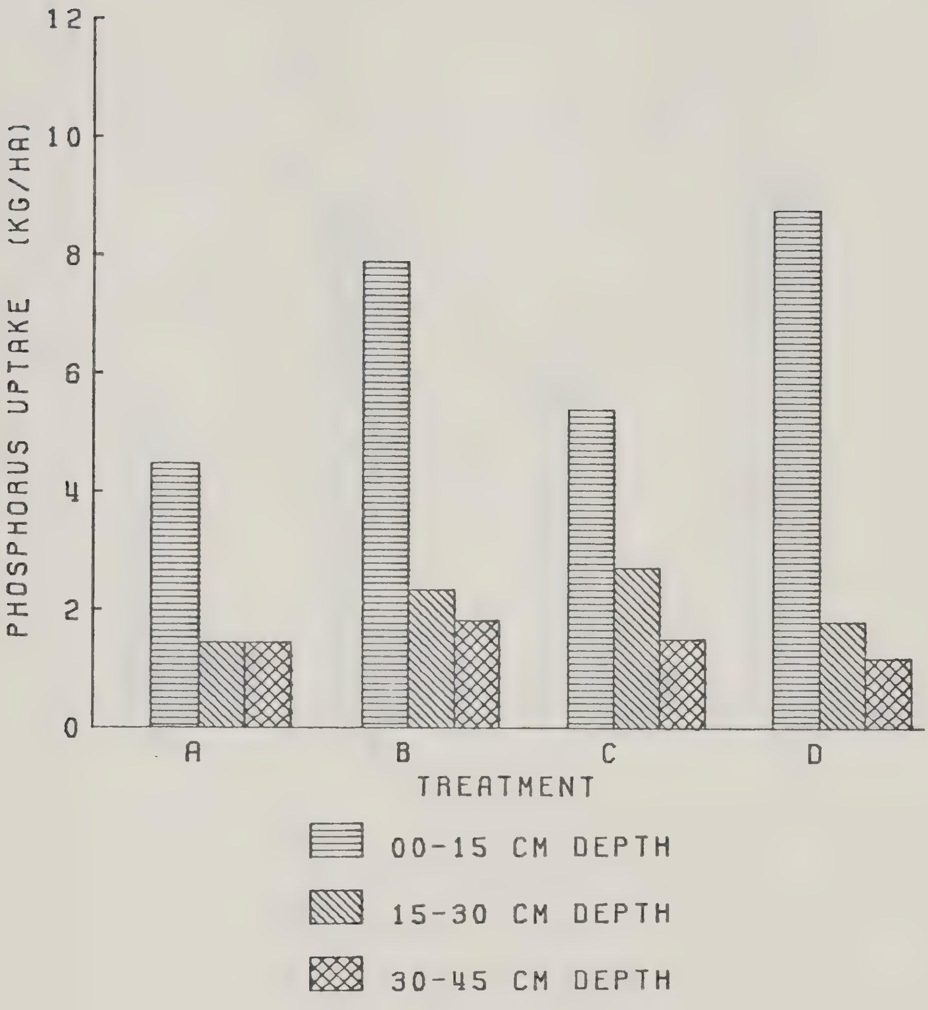



Figure 8 P uptake from three depths by barley for the 1976 Vegreville site using the Olsen method to estimate exchangeable P. The four treatments are; A non-irrigated, 10 kg P/ha; B non-irrigated, 40 kg P/ha; C irrigated, 10 kg P/ha; D irrigated, 40 kg

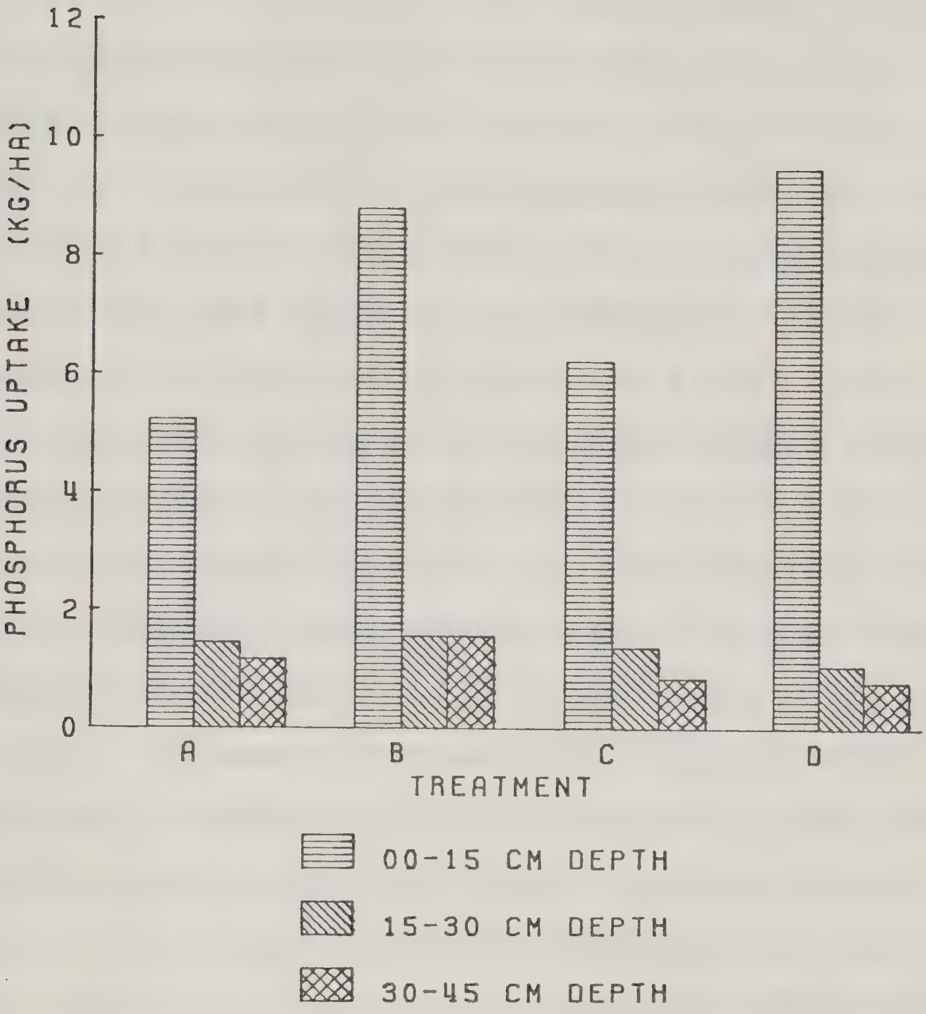



Figure 9 P uptake from three depths by barley for the 1976 Vegreville site using the Miller and Axley method to estimate exchangeable P. The four treatments are: A non-irrigated, 10 kg P/ha; B non-irrigated, 40 kg P/ha; C irrigated, 10 kg P/ha; D irrigated, 40 kg P/ha.

into the lower horizons and could be responsible for a decrease in phosphorus uptake from 15-45 cm depth. The Ellerslie and Breton sites do not have the same physical problems as the Vegreville site and additional moisture should penetrate until such time as the soil above the wetting front reaches field capacity. The moisture contents (Table 3) reveal that both irrigations would have brought the soil at both Breton and Ellerslie to field capacity to a depth of at least 45 cm. (Field capacities are given in Appendix 1.) In the case of Breton this would have resulted in a substantial difference in profile moisture content between irrigated and non-irrigated treatments after both irrigations. At the Ellerslie site the irrigation would have altered moisture content of the subsoil for the first irrigation but would have had little effect at the second irrigation because it was near field capacity before irrigation. Breton, where irrigation should have caused the greatest change in profile moisture content, showed a 40% increase in the mean uptake of phosphorus from the 15-45 cm depth (Fig. 4 and 5). Barley at Ellerslie had an apparent increase in phosphorus uptake from the 15-45 cm of 25% on the irrigated treatment (Fig. 6 and 7). Although the irrigation effects were not significant at either Breton or Ellerslie it appears that increased moisture in the 15-45 cm depth may have resulted in a change in uptake from that depth.

4.1.2.2 Phosphorus Fertilizer

The fertilizer phosphorus treatment had no significant effect on uptake of phosphorus by barley from the 15-45 cm depth. However, as with the irrigation treatment, plot variability may have rendered actual effects nonsignificant.

The Vegreville site showed the least observable effect of phosphorus fertilizer treatment on the uptake of subsurface (15-45 cm) phosphorus. The data indicated that the high phosphorus treatment resulted in an apparent 5% increase in uptake of subsoil phosphorus over the low phosphorus treatment (Fig. 8 and 9). It would be expected that the Vegreville site would show the least effect of treatment on root distribution because the Bnt horizon exerts a controlling influence on root distribution. The reason the Vegreville site shows a slight increase in uptake from depth while the other sites show decreases probably relates to the low phosphorus status of the Vegreville site. It is commonly stated that phosphorus must be adequate to ensure adequate root growth. It is probable that the available phosphorus on the low phosphorus treatment was suboptimal for root growth. This explanation gains credibility when the magnitude of the fertilizer response is considered. Conversely, Breton and Ellerslie sites experienced an apparent decrease in uptake of subsoil phosphorus of 12% and 39% respectively (Fig. 4-7). It is probable that the Ellerslie and Breton sites, with their much lower fertilizer response, had sufficient available

phosphorus on the low level phosphorus treatment to develop a deep root system. The additional phosphorus available in the surface 15 cm on the high phosphorus treatment may have encouraged proliferation of roots in the surface 15 cm of the soil, thereby decreasing availability of plant assimilates for growth of deeper roots. This would explain the apparent results but the extreme variability of uptake values leaves this conclusion open to question. Overall the data indicated that subsoil phosphorus rapidly decreased in importance with the application of fertilizer phosphorus. Under the low phosphorus treatment the barley crops took up 72, 73 and 66 per cent of their phosphorus from the upper 15 cm of soil at Breton, Ellerslie and Vegreville respectively (Fig. 5-9). Under the high phosphorus treatment phosphorus uptake from the upper 15 cm was 85, 80 and 75 per cent at Breton, Ellerslie and Vegreville respectively (Fig. 5-9). The decrease in relative importance of subsoil P with application of fertilizer phosphorus agrees with the results of other workers (Richter _et al_., 1977).

The results suggest that barley grown on the Vegreville site obtained more phosphorus from subsoil than barley grown at the other sites. This result appears somewhat incongruous when the effect of the Bnt horizon on root growth is considered, however, there is supporting evidence. Root distributions obtained using the "$^{32}P$ plant injection method" indicated that barley grown at the Vegreville site tended to have a higher proportion of its roots below 15 cm

than at the other sites (Table 6). Also, soil moisture data taken at harvest shows that the Vegreville site had moisture contents below the -15 bar percentage in the 15-45 cm depth, which suggestes that there was root activity at that depth (Table 3). This was not the case at the other sites. During the last six weeks of the growing season rainfall was lower at Vegreville than at the other sites. This may have "encouraged" the barley at the Vegreville site to make more use of subsoil moisture and nutrients than was the case at the other sites. Also there is evidence to suggest that a high bulk density such as is encountered in the Bnt horizon of a Solonetz soil may result in increased uptake of phosphorus (Subbiah et al., 1968).

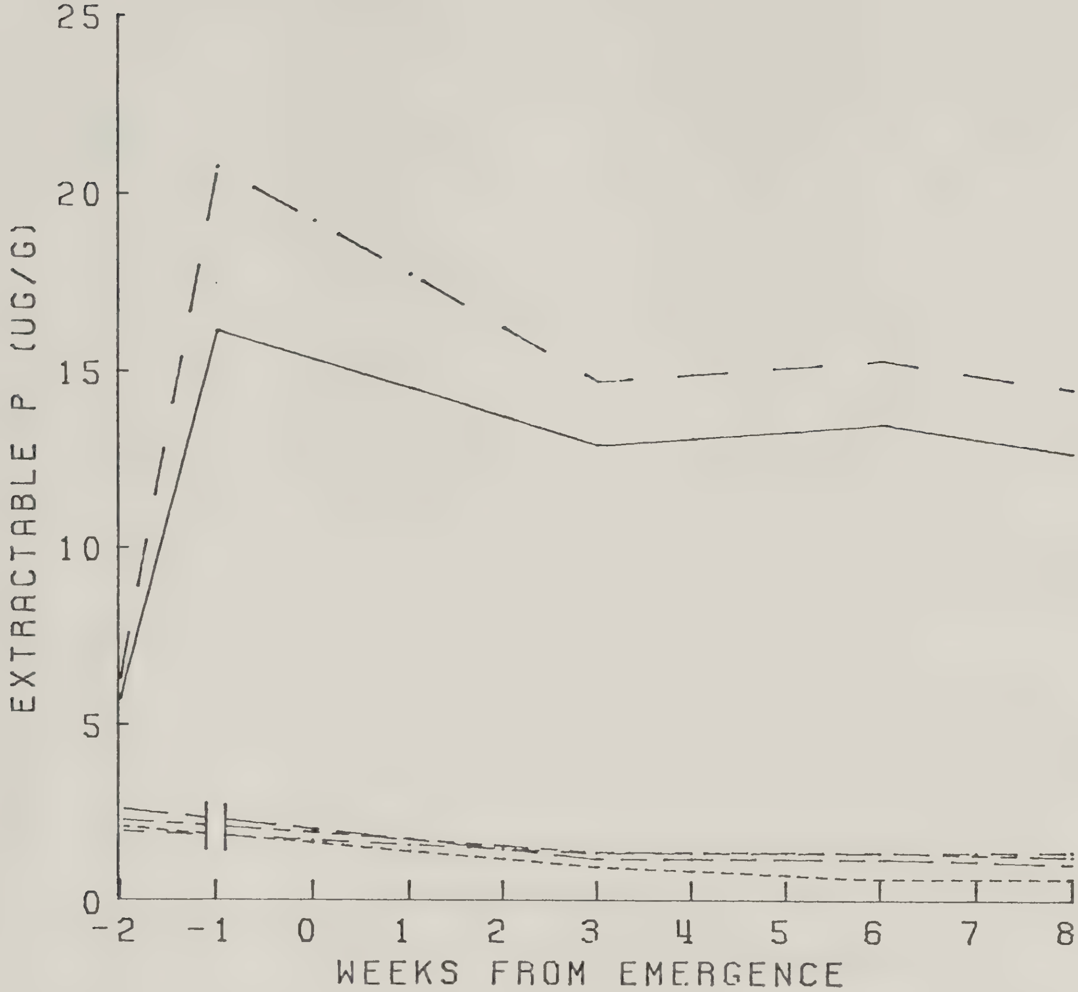
## 4.2 Field Experiments 1977

The 1977 field experiments were designed to provide further information on the uptake of phosphorus from the subsoil by barley. The design was such that uptake could be followed through the season with concurrent plant and soil sampling. In this manner it was possible to get a more accurate estimate of the changes in available phosphorus during the growing period for each site (Fig. 10-11). During the previous year's work it had become clear that site variability must account for anomalous data. The degree of variability of the sites chosen for the second year's study is readily apparent in the values of extractable phosphorus and pH for soil samples taken prior to fertilization and

Table 6 Barley root distribution 1976 field studies. *

| Site | Depth | Radius (cm) 0 | 15 | 30 |
|---|---|---|---|---|
| Breton | 0-15 | 93 | 100 | 0 |
| | 15-30 | 5 | 0 | 0 |
| | 30-45 | 1 | 0 | 0 |
| | 45-60 | 1 | 0 | 0 |
| Ellerslie | 0-15 | 91 | 84 | 100 |
| | 15-30 | 4 | 16 | 0 |
| | 30-45 | 3 | 0 | 0 |
| | 45-60 | 2 | 0 | 0 |
| Vegreville | 0-15 | 69 | 89 | 100 |
| | 15-30 | 26 | 6 | 0 |
| | 30-45 | 5 | 5 | 0 |
| | 45-60 | 0 | 0 | 0 |

* The roots present at each depth and radius are expressed as a percentage of the total amount of roots at that radius.




Olsen extraction | Miller and Axley extraction

——— 00-15 CM DEPTH | — — 00-15 CM DEPTH

— — —· 15-30 CM DEPTH | ----· 15-30 CM DEPTH

-------- 30-45 CM DEPTH | —— — — 30-45 CM DEPTH

Figure 10 Extractable soil phosphorus over the season for the 1977 Ellerslie site using the Miller and Axley and Olsen extractions.

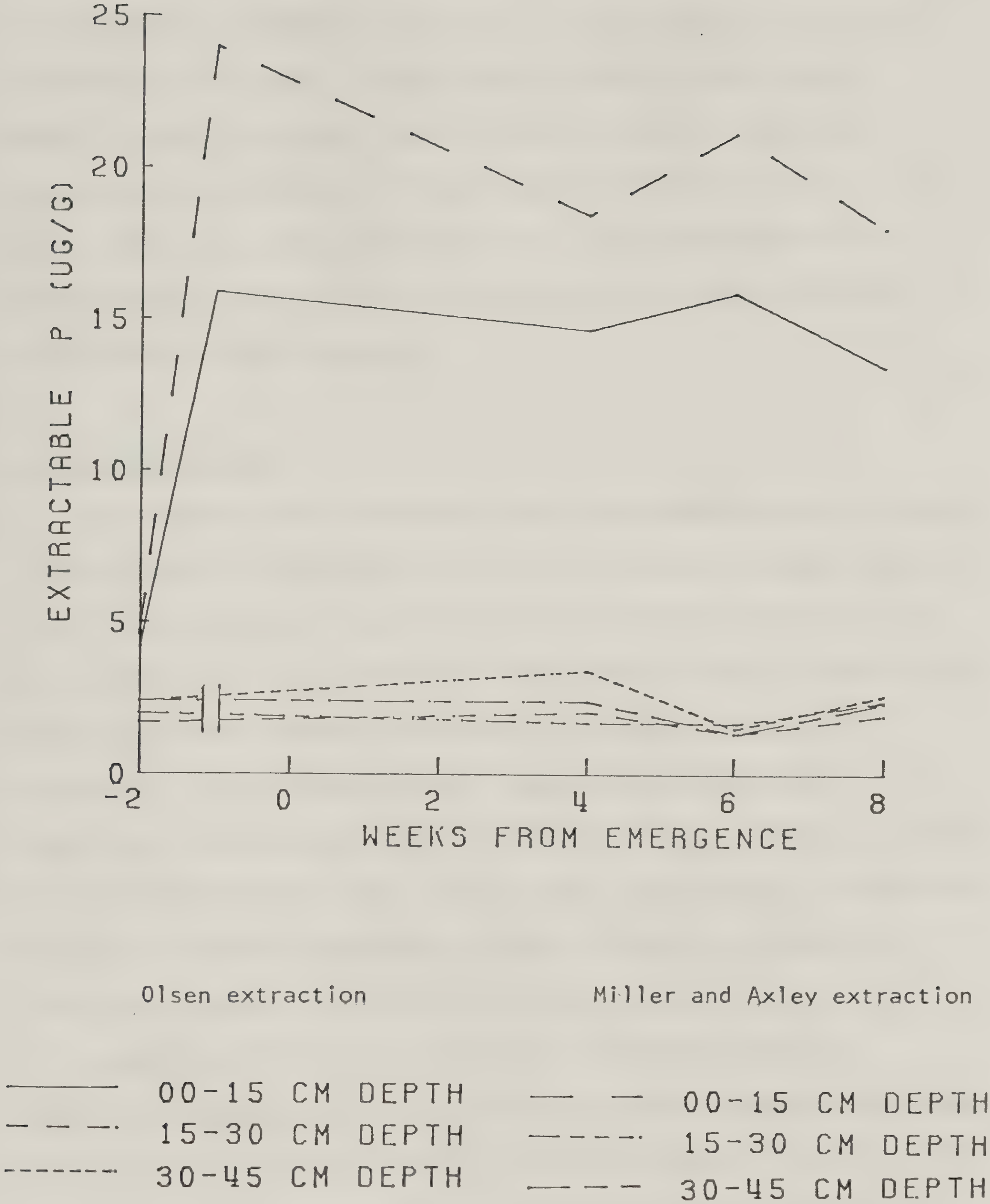



Figure 11 Extractable soil phosphorus over the season for the 1977 Vegreville site using the Miller and Axley, and Olsen extractions.

seeding (Fig. 12-17). It must be remembered that these sites were chosen because they did not exhibit a high degree of variability in profile features. It is apparent that the chemistry of a soil is often much more variable than morphological features would make it appear. This is particularily evident at the Vegreville study site. It was hoped that the increased level of site characterization would remove some of the variability and allow for more confidence in the results.

### 4.2.1 Plot Yields

In general the Vegreville site had substantially higher yields than the Ellerslie site at all harvest dates (Tables 7-8). The reason for the substantial yield differences are of interest in the context of this study. The Ellerslie site contained more profile moisture at seeding than the Vegreville site (Table 9-10), however the Vegreville site received considerably more rainfall between seeding and the first harvest (Fig. 18). Overall the two sources of moisture at the two sites provided a similar amount of moisture. Water use, based on changes in soil moisture and rainfall was approximately 90 mm and 72 mm at Vegreville and Ellerslie respectively prior to the first harvest. Although both sites used approximately the same amount of water on a weekly basis, the Ellerslie crop obtained over 60% of its moisture from the soil at depths greater than 15 cm. The Vegreville crop obtained only about 35% of its moisture from

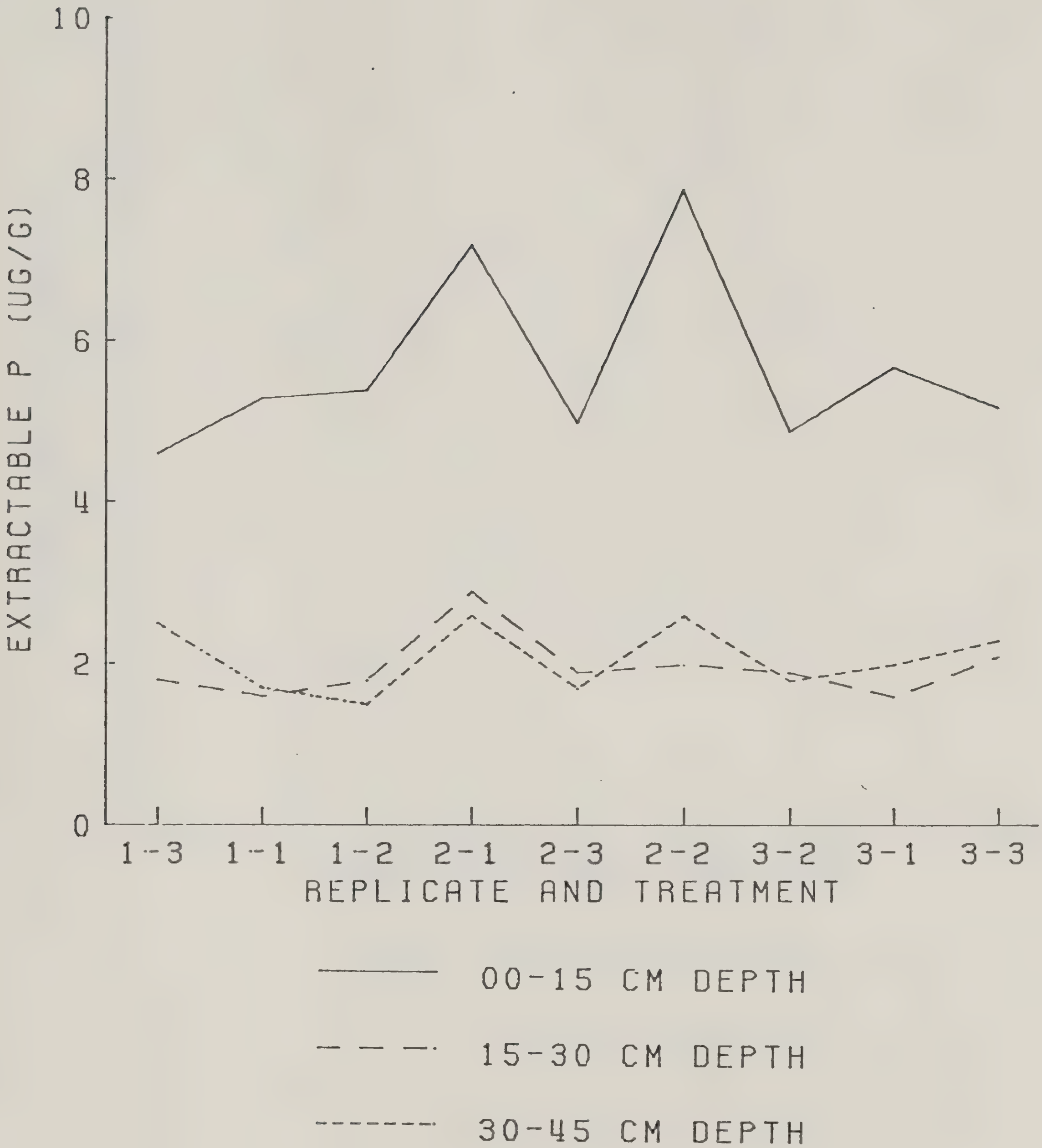



Figure 12 Distribution of extractable soil P (Olsen method) at the 1977 Ellerslie site.

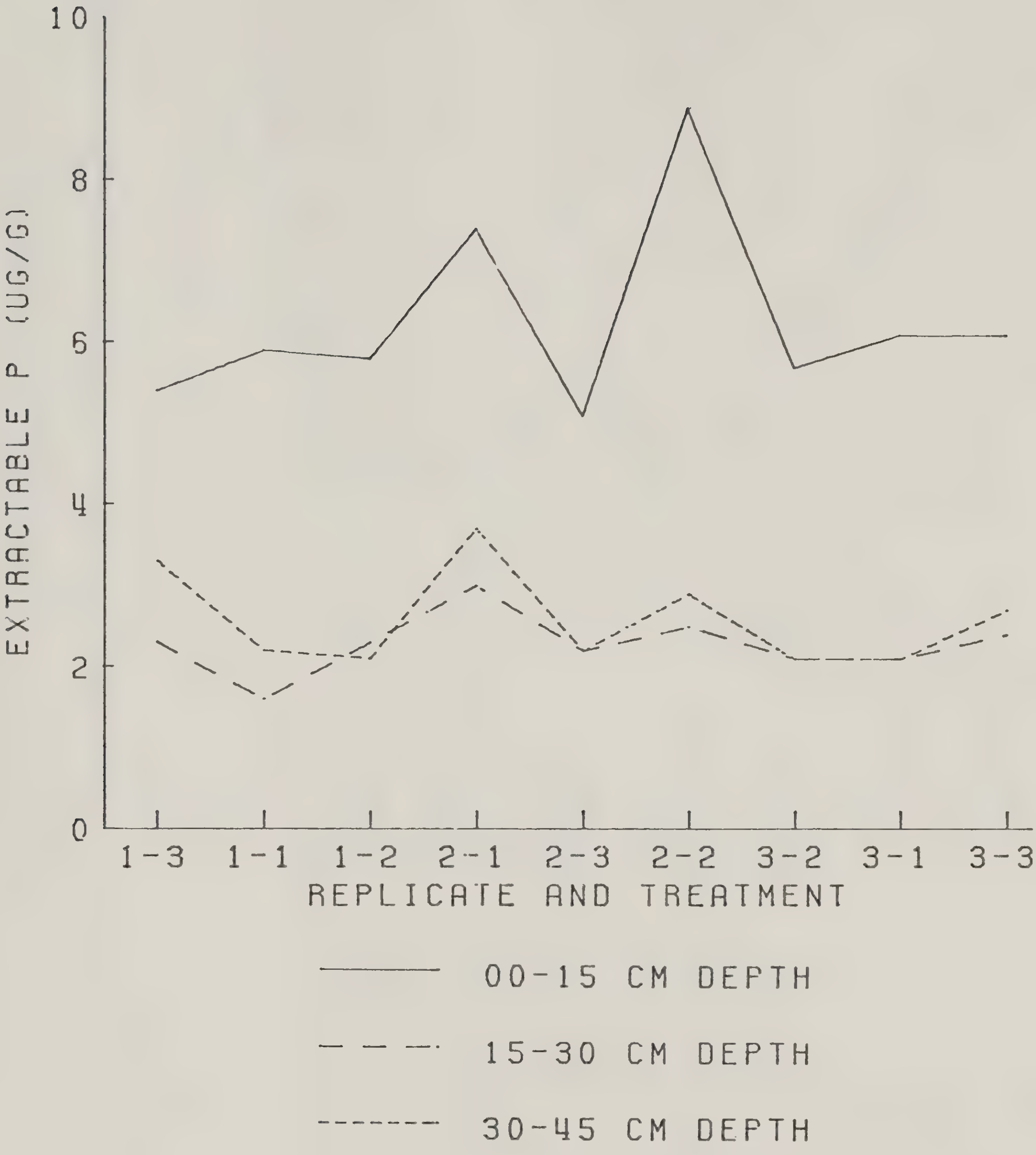



Figure 13 Distribution of extractable soil P (Miller and Axley method) at the 1977 Ellerslie site.

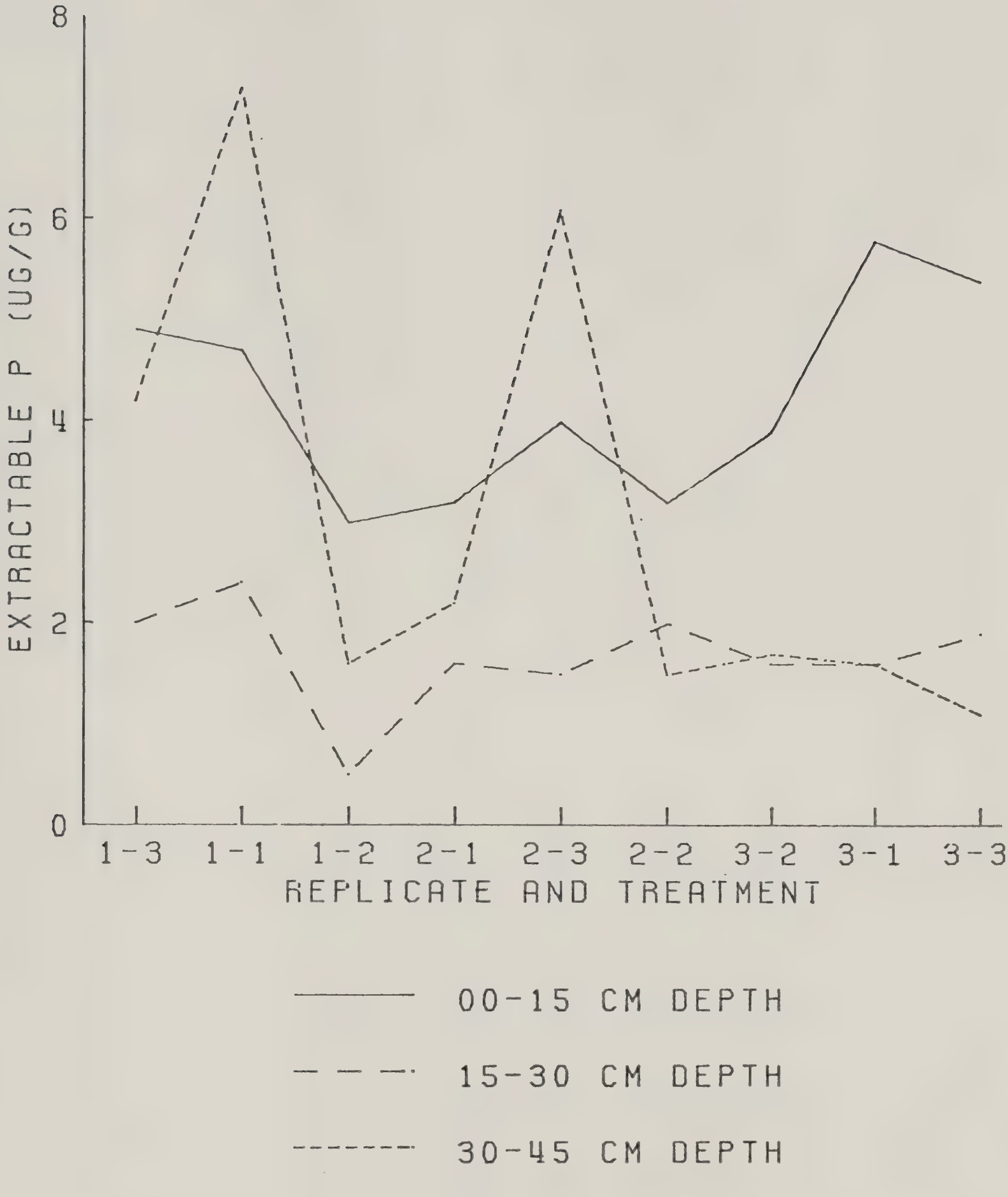



Figure 14 Distribution of extractable soil P (Olsen method) at the 1977 Vegreville site prior to fertilization.

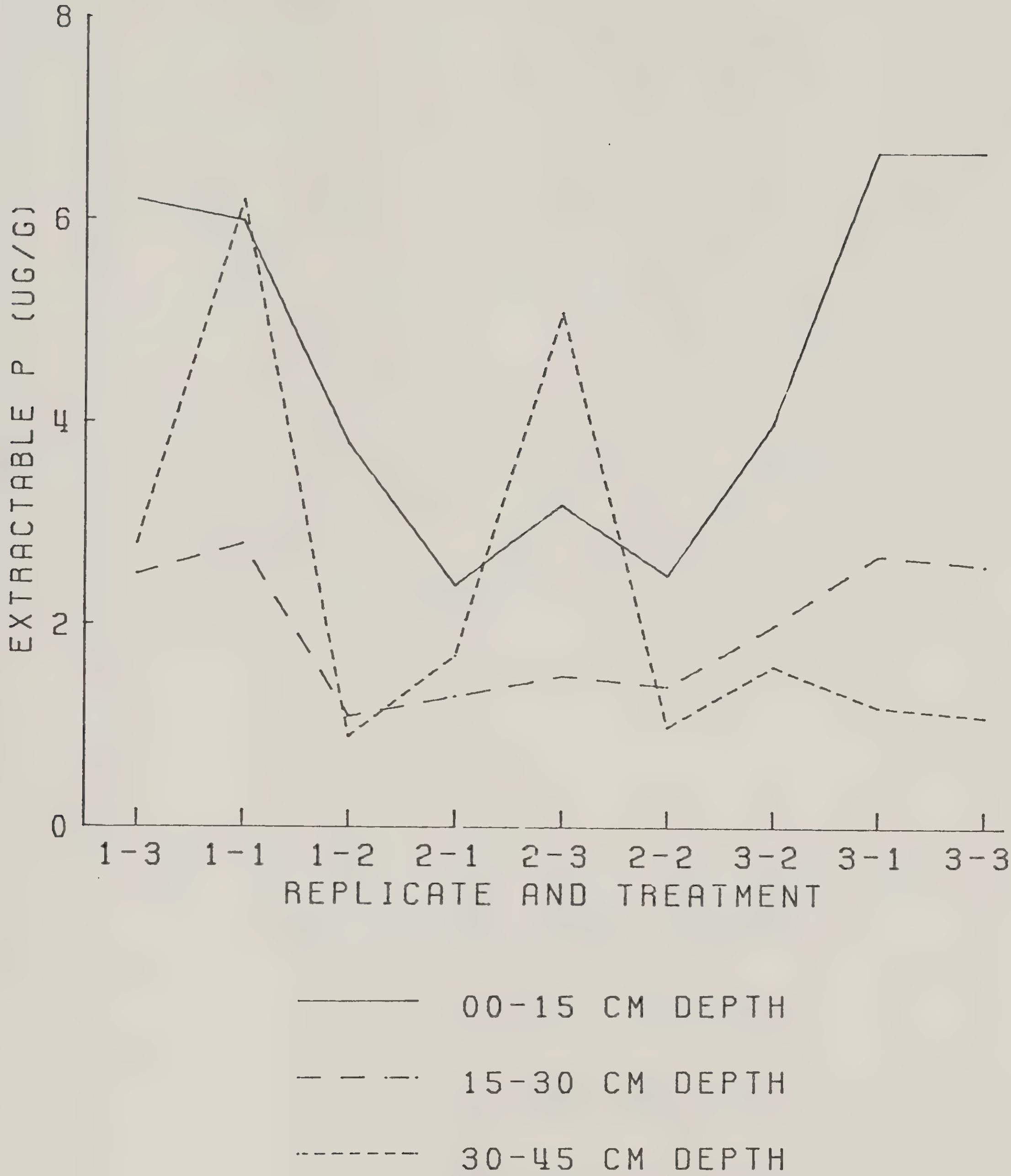



Figure 15 Distribution of extractable P (Miller and Axley method) at the 1977 Vegreville site prior to fertilization.

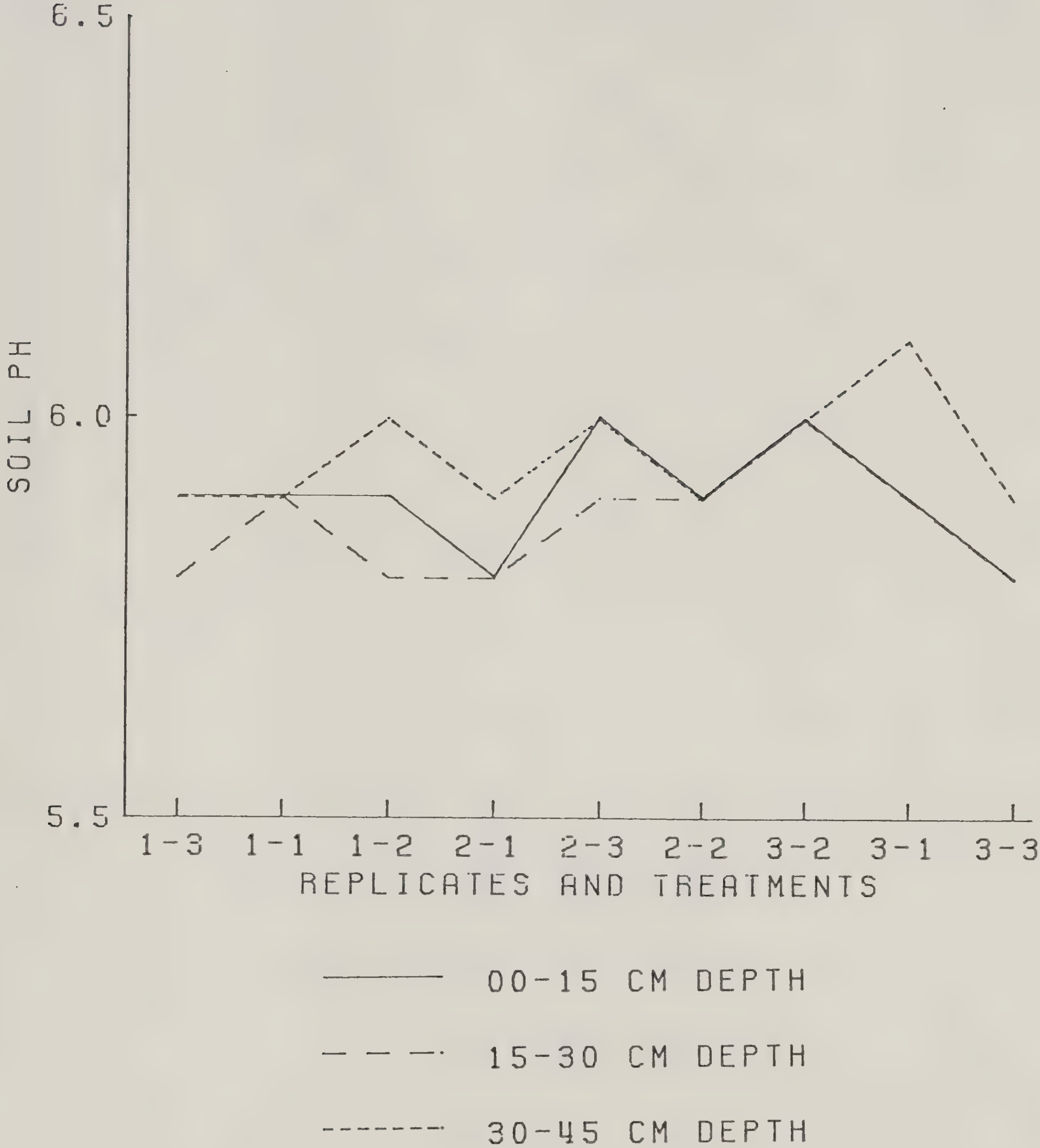



Figure 16 Distribution of pH (1:2.5) at the 1977 Ellerslie site.

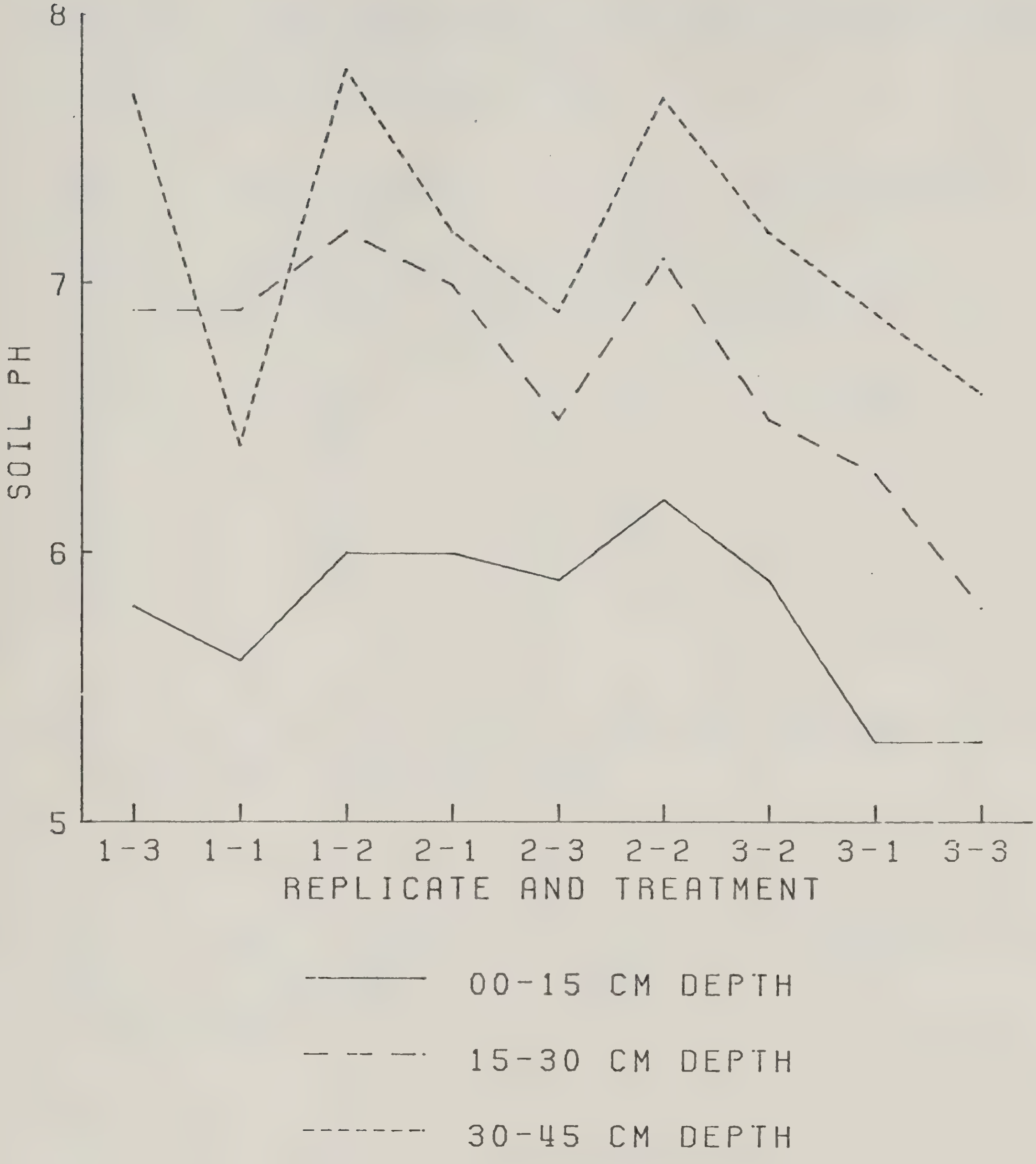



Figure 17 Distribution of pH (1:2.5) at the 1977 Vegreville site.

Table 7 Phosphorus uptake, yield and P content of barley for the 1977 Ellerslie study.

| Time days | Plant Material tonne/ha | P Uptake kg/ha | P Concentration % |
|---|---|---|---|
| 21 | 0.80 | 2.8 | 0.34 |
| 42 | 2.47 | 6.0 | 0.24 |
| 56 | 4.35 | 9.0 | 0.21 |
| 74 | 3.18 | 7.1 | 0.22 |

Table 8 Phosphorus uptake, yield and P content of barley for the 1977 Vegreville study.

| Time days | Plant Material tonne/ha | P Uptake kg/ha | P Concentration % |
|---|---|---|---|
| 28 | 2.01 | 5.4 | 0.27 |
| 42 | 4.23 | 10.1 | 0.24 |
| 56 | 6.36 | 12.2 | 0.19 |
| 73 | 4.17 | 9.39 | 0.22 |

Table 9 Soil moisture at the Ellerslie site during the 1977 season.

| Depth cm | Time: Seeding | Harvest 1 | Harvest 2 | Harvest 3 |
|---|---|---|---|---|
| 0-15 | 37.9 | 21.1 | 33.9 | 20.1 |
| 15-30 | 39.7 | 22.1 | 24.6 | 21.0 |
| 30-45 | 29.5 | 21.9 | 15.6 | 15.9 |
| 45-60 | 22.2 | 21.1 | 14.7 | 15.5 |
| 60-90 | 19.3 | 21.6 | 16.8 | 17.9 |

Table 10 Soil moisture at the Vegreville site during the 1977 season.

| Depth cm | Time: Seeding | Harvest 1 | Harvest 2 | Harvest 3 |
|---|---|---|---|---|
| 0-15 | 34.0 | 19.0 | 14.5 | 18.4 |
| 15-30 | 25.1 | 14.4 | 12.5 | 13.3 |
| 30-45 | 20.5 | 16.3 | 14.4 | 13.7 |
| 45-60 | 14.0 | 13.5 | 14.0 | 15.3 |
| 60-90 | 12.8 | 12.5 | 10.7 | 11.8 |

below 15 cm. Presumably the 0-15 cm depth at Vegreville, because of its more favourable moisture status, would have been conducive to nutrient uptake more of the time than the 0-15 cm depth at Ellerslie which was dry much of the time prior to the first harvest. The poor crop growth at the Ellerslie site prior to the first harvest appears to indicate that the subsoil is a poor source of plant nutrients. The Ellerslie site also developed a weed infestation which affected the growth of the barley crop, but at the first harvest the problem was just becoming evident. It appeared that the weed infestation was the result, rather than the cause of poor initial growth at the Ellerslie site.

Subsequent to the first harvest, rainfall appeared to be adequate at both sites for the remainder of the growing season (Fig. 18). Total plant material and phosphorus uptake at the Ellerslie site after 56 days was about 70% of that at Vegreville (Tables 7 and 8). The main reason for the difference was probably the weed infestation at the Ellerslie site.

### 4.2.2 Phosphorus Uptake with Respect to Depth

Barley grown at the Vegreville site appeared to obtain more phosphorus from below 15 cm at all harvest dates than did the Ellerslie crop. Subsoil phosphorus uptake was greater at Vegreville in both relative and absolute terms (Fig. 19-22). The data indicated subsoil phosphorus is of

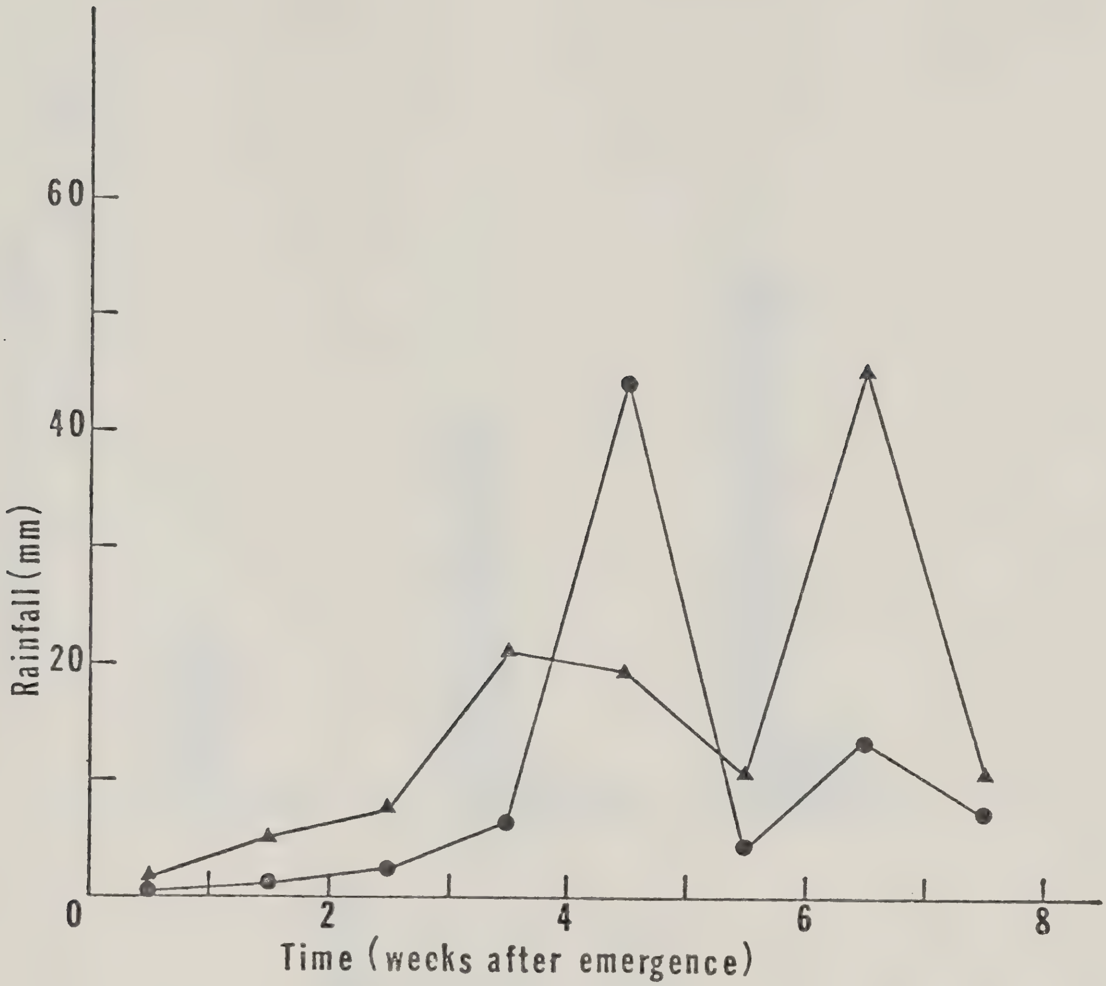



Figure 18 Rainfall patterns during the 1977 field studies at Ellerslie ( ● ) and Vegreville ( ▲ ).

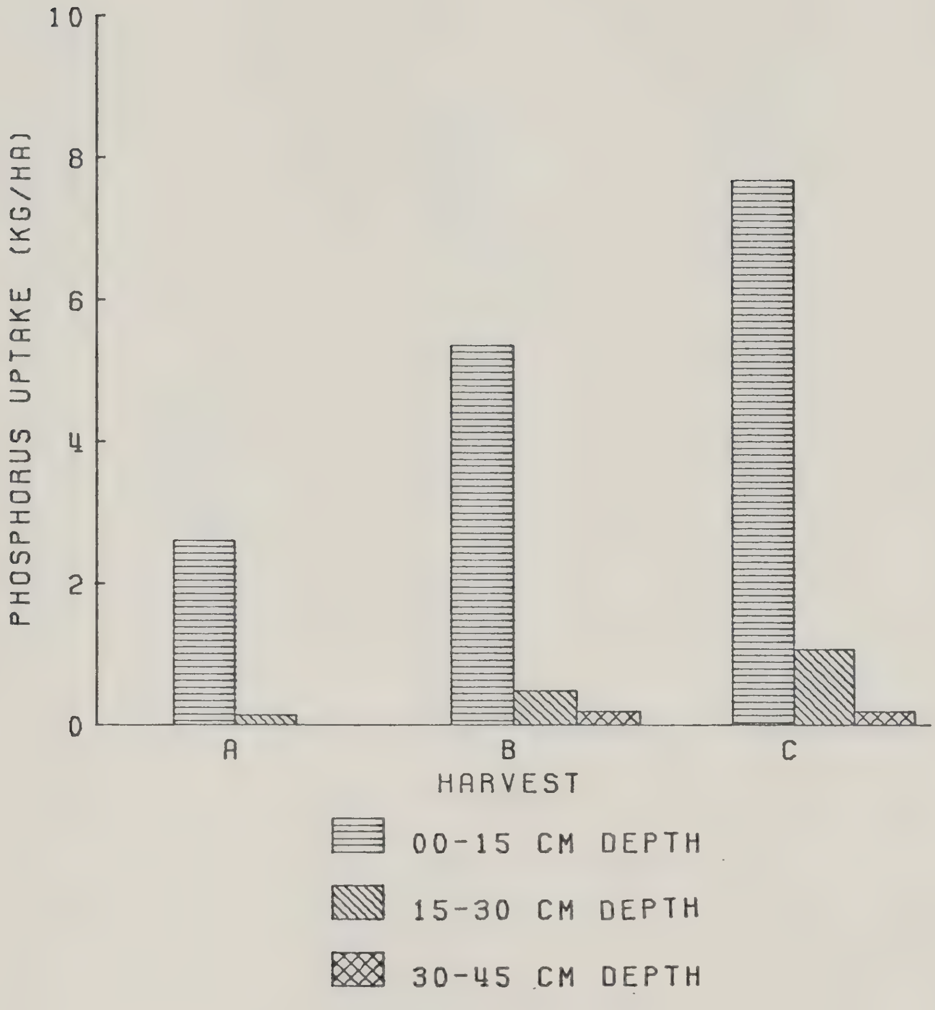



Figure 19 P uptake from three depths by barley for the 1977 Ellerslie site using the Olsen method to estimate exchangeable P. The three harvest dates are: A 21 days, B 42 days, C 56 days.

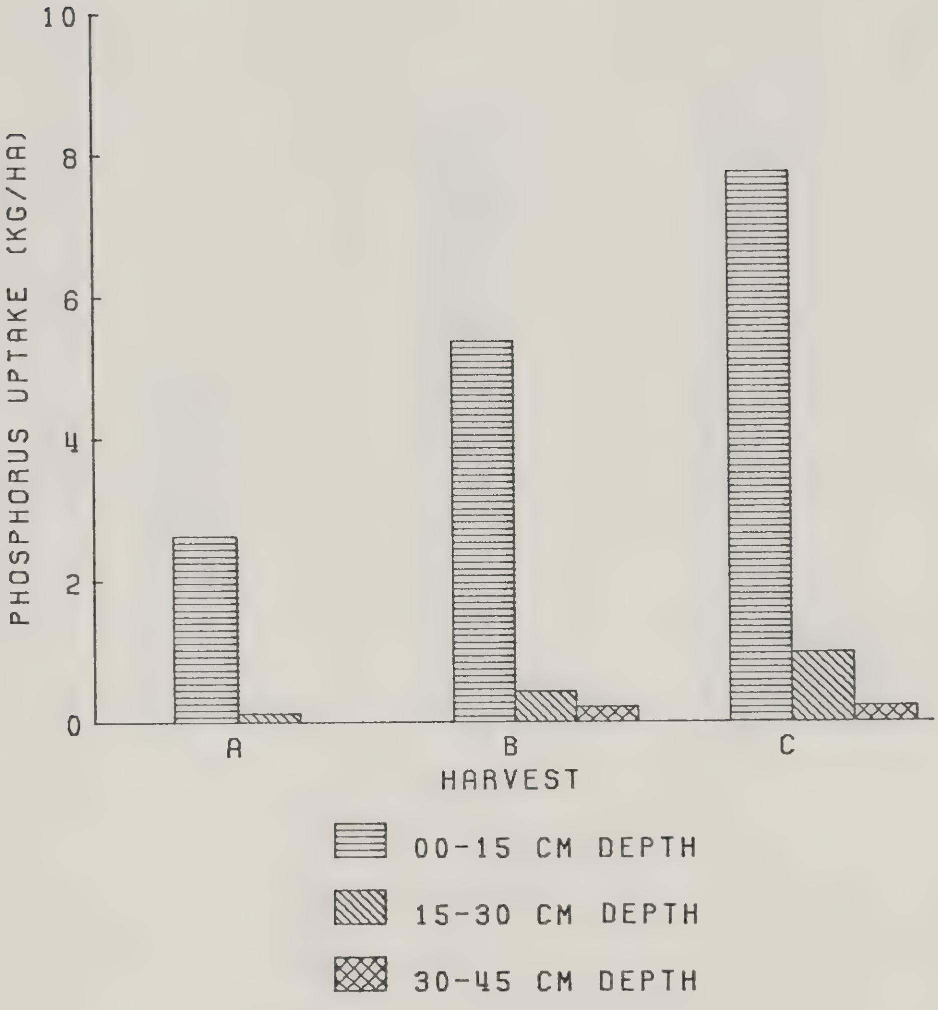



Figure 20 P uptake from three depths by barley for the 1977 Ellerslie site using the Miller and Axley method to estimate exchangeable P. The three harvest dates are: A 21 days, B 42 days, C 56 days.

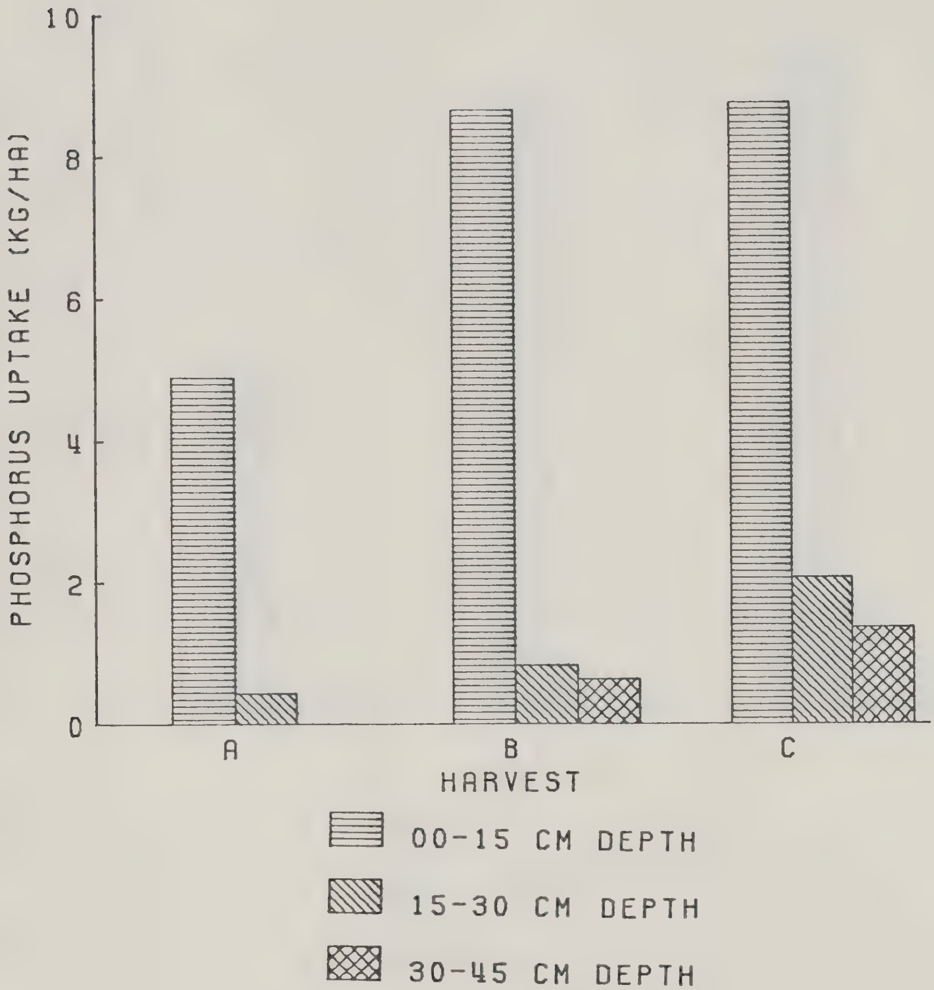



Figure 21 P uptake from three depths by barley for the 1977 Vegreville site using the Olsen method to estimate exchangeable P. The three harvest dates are: A 28 days, B 42 days, C 56 days.

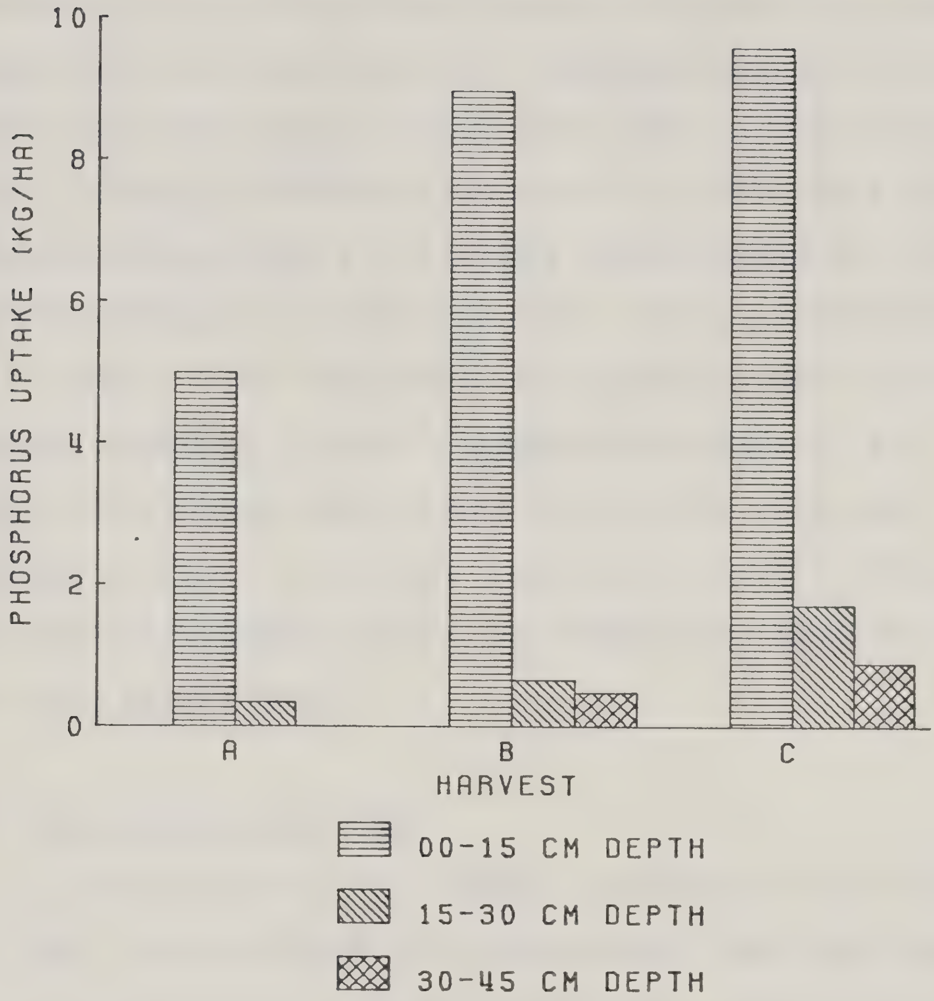



Figure 22 P uptake from three depths by barley for the 1977 Vegreville site using the Miller and Axley method to estimate exchangeable P. The three harvest dates are: A 28 days, B 42 days,

limited importance during the early part of the season but becomes more important as the plant develops. At the Ellerslie site uptake from below 15 cm increased from approximately 5% at the first harvest to 14% at the final harvest. At the Vegreville site phosphorus uptake from the subsoil was approximately 7% of the total at the first harvest. Subsoil phosphorus increased in importance and comprised approximately 25% of the total uptake for the Vegreville crop by the third harvest. The root distribution data at eight weeks complements the uptake study because Vegreville appears to have a higher percentage of its biologically active roots below 15 cm depth than does Ellerslie (Tables 11 and 12). In general the data from the 1977 field experiments appear to support the findings of the 1976 field experiments.

#### 4.2.3 $^{32}P$ Uptake Over Time

In an attempt to gain further information on P uptake over time a variation of the calculations used previously was carried out on the second year's data. This calculation did not require the use of $^{32}P$ specific activity in the soil and thereby bypassed the problems encountered obtaining specific activity. The purpose of this calculation was to obtain a relative measurement of the amount of phosphorus absorbed from the labelled volume at each of the three harvests. The values were obtained by multiplying $^{32}P$ specific activity of P in the microplot plant samples by the

Table 11 Barley root distribution for the 1977 field studies at Ellerslie.*

| Time days | Depth | Radius (cm) 0 | 15 | 30 |
|---|---|---|---|---|
| 21 | 0-15 | 34.8 | 4.8 | 0 |
| | 15-30 | 12.1 | 3.2 | 0 |
| | 30-45 | 44.8** | 0 | 0 |
| 42 | 0-15 | 77.9 | 10.6 | 3.3 |
| | 15-30 | 1.6 | 0 | 2.4 |
| | 30-45 | 3.8 | 0 | 0 |
| 56 | 0-15 | 93.1 | 0.4 | 0.1 |
| | 15-30 | 3.7 | 0.3 | 0.1 |
| | 30-45 | 1.1 | 0 | 0.1 |
| | 45-60 | 0.6 | 0.3 | 0.1 |

* The roots present at each depth and radius are expressed as a percentage of the total amount of roots.

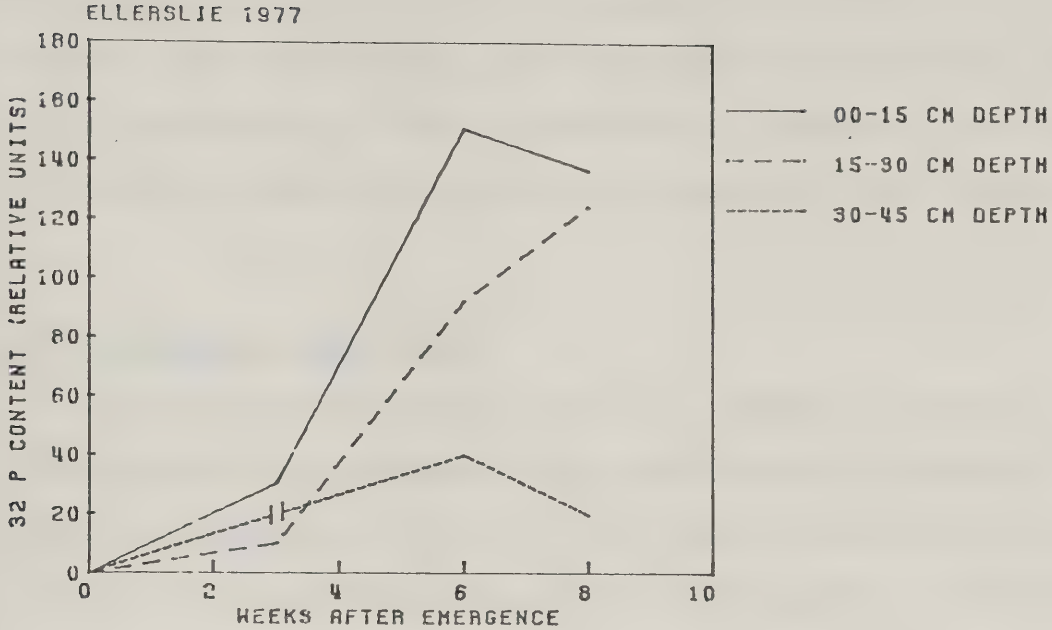
** Note apparent error in determination.

Table 12 Barley root distribution for the 1977 field studies at Vegreville.*

| Time | Depth | Radius (cm) | | |
|---|---|---|---|---|
| days | cm | 0 | 15 | 30 |
| 28 | 0-15 | 94.8 | 1.3 | 0 |
| | 15-30 | 1.3 | 0 | 0 |
| | 30-45 | 1.8 | 0 | 0 |
| | 45-60 | 0.7 | 0 | 0 |
| 42 | 0-15 | 95.1 | 1.8 | 0 |
| | 15-30 | 0.9 | 1.4 | 0 |
| | 30-45 | 0 | 0.8 | 0 |
| | 45-60 | 0 | 0 | 0 |
| 56 | 0-15 | 78.4 | 6.6 | 0 |
| | 15-30 | 6.3 | 1.2 | 0 |
| | 30-45 | 1.5 | 2.1 | 0 |
| | 45-60 | 2.0 | 0 | 0 |

* The roots present at each depth and radius are expressed as a percentage of the total amount of roots.

total phosphorus in the above ground portion as determined from the yield plots. The values are relative but all hold the same relationship to the actual $^{32}P$ activity in the above ground portion of barley crop. It will be noticed that there is a large decrease in the total counts present in the above ground portion at Vegreville from the first harvest to the third havest (Fig. 23 ). This apparent decrease is most evident in the barley from the microplots labelled in the 0-15 cm depth. The average values for $^{32}P$ present in barley from the microplots labelled at the 15-30 cm depth shows little change between 4 and 8 weeks while the 30-45 cm depth exhibits a slight decrease. Although the high variability between replicates results in none of the changes in $^{32}P$ content reaching significance, it is important to recognize that the amount of $^{32}P$ present in the plant material exhibits the opposite trend to what would be expected if barley plants are in fact "zero sinks" for phosphorus. Ellerslie does not exhibit as large of a decrease in $^{32}P$ activity as the Vegreville site but it does show an apparent decrease after 6 weeks. The data suggest that the barley crop at Vegreville lost more absorbed phosphorus back to the soil than the crop at grown at the Ellerslie site. If that was the case, a comparison of the relative importance of subsoil phosphorus at the two sites may be misleading. It is important to recognize that if barley plants lose a large portion of previously absorbed phosphorus to the soil, the values obtained on uptake of phosphorus from any depth are a



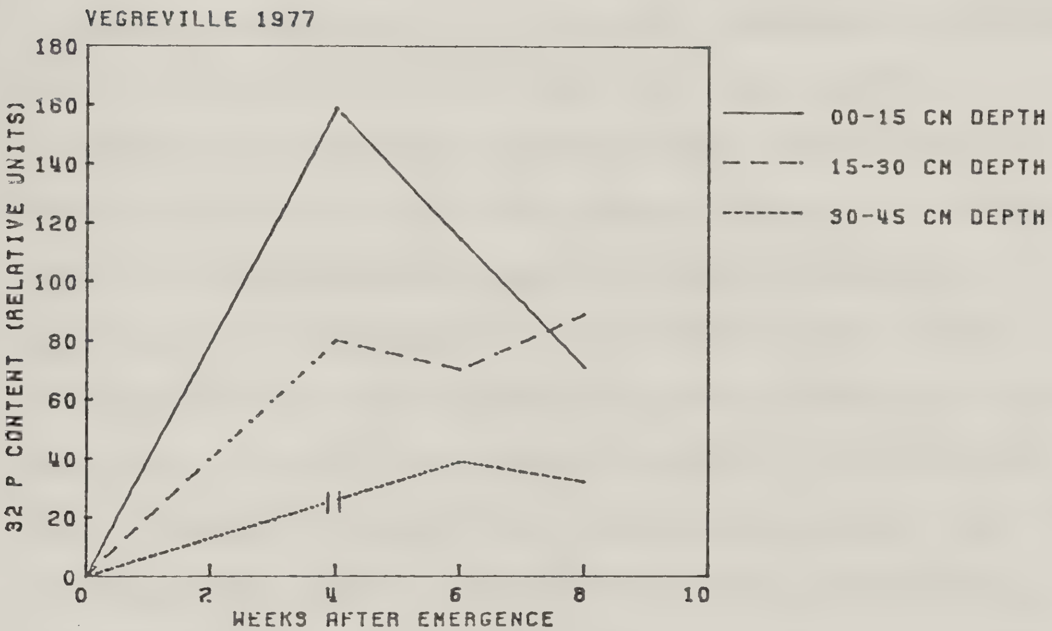




Figure 23 $^{32}P$ content in the above ground portion of barley over time at the 1977 Ellerslie and Vegreville sites.

measurement of the phosphorus present in the plant at the time of the measurement. Therefore the uptake results may not be indicative of the importance of phosphorus in any given soil volume to plant growth over the entire season.

### 4.3 Greenhouse Study 1977

The greenhouse study served as a means of further quantifying the phosphorus supplying ability of subsoil. The subsoil samples were from the 1976 field sites but the close proximity of the 1977 sites allows the results to be applied to the sites for both years. It is apparent that the subsoils evaluated in this study have a very limited ability to supply phosphorus to barley under greenhouse conditions (Table 13). Where all nutrients with the exception of phosphorus were supplied in presumably adequate amounts total phosphorus in the above ground portion of the barley plants was considerably lower for subsoils than for topsoils. Total phosphorus in the above ground plant material grown on unfertilized subsoils, from the 15-30 cm and 30-45 cm depths, was approximately 25, 17 and 9 % of that for barley grown on the unfertilzed surface soil for the Vegreville, Breton and Ellerslie sites respectively. This would appear to indicate that the subsoils studied cannot supply phosphorus to barley at rates approaching those of the surface soils from the same sites. However the inability of the subsoil to supply phosphorus at rates similar to the surface soil appears to be related to the

Table 13 Yield, P uptake and P concentration of barley plants and extractable P of soil for the 1977 greenhouse experiment.

| Site | Depth | P | Dry Matter Yield | Total P Uptake | Plant P Conc. | Extractable P* M&A | Extractable P* Olsen |
|---|---|---|---|---|---|---|---|
| | cm | treatment | g/pot | mg/pot | ug/g | mg/pot | mg/pot |
| Breton | 0-15 | +P | 1.9 | 3.8 | 2000 | 32 | 20 |
| | | -P | 1.4 | 1.8 | 1290 | 22 | 14 |
| | 15-30 | +P | 1.3 | 1.9 | 1490 | 13 | 11 |
| | | -P | 0.47 | 0.31 | 660 | 5.5 | 4.1 |
| | 30-45 | +P | 1.1 | 1.5 | 1390 | 11 | 10 |
| | | -P | 0.45 | 0.30 | 670 | 4.4 | 4.1 |
| Ellerslie | 0-15 | +P | 1.3 | 3.0 | 2340 | 18 | 14 |
| | | -P | 0.88 | 1.7 | 1960 | 10 | 8.1 |
| | 15-30 | +P | 0.97 | 1.3 | 1390 | 16 | 11 |
| | | -P | 0.19 | 0.13 | 680 | 3.7 | 2.8 |
| | 30-45 | +P | 1.1 | 1.4 | 1290 | 14 | 12 |
| | | -P | 0.29 | 0.19 | 650 | 2.3 | 1.7 |
| Vegreville | 0-15 | +P | 1.8 | 2.8 | 1550 | 19 | 10 |
| | | -P | 0.71 | 1.2 | 1700 | 9.4 | 5.2 |
| | 15-30 | +P | 2.7 | 6.4 | 2400 | 31 | 21 |
| | | -P | 0.38 | 0.29 | 750 | 4.6 | 3.0 |
| | 30-45 | +P | 2.5 | 7.7 | 3100 | 22 | 25 |
| | | -P | 0.43 | 0.32 | 760 | 4.1 | 4.4 |

* Extractable soil phosphorus was determined on the soils at the end of the experiment.

amount of phosphorus present, not differences in the forms of phosphorus compounds. Correlations between total phosphorus in the above ground portion of the barley plants and extractable phosphorus by the Olsen and Miller and Axley methods are significant ($P \leq 0.01$) (Fig. 24). The correlations and regressions indicate that given a specific level of extractable phosphorus barley is able to extract essentially the same amount of phosphorus regardless of the depth from which the soil was taken. It seems justifiable to conclude that there is a consistent relationship between extractable phosphorus and plant available phosphorus that is independent of depth effects. This observation is of particular importance as it tends to justify the approach used in the calculation of uptake from different soil layers. Since extractable phosphorus is highly correlated with the uptake of phosphorus from soil from all depths and since plants will absorb only phosphorus in solution, it seems justifiable to conclude that extractable phosphorus is well correlated with the total pool of labile phosphorus present in the soil. Presumably $^{32}P$ added to soil can exchange only with labile phosphorus that is able to enter the solution phase. It therefore seems justifiable to use extractable phosphorus as a measure of exchangeable phosphorus.

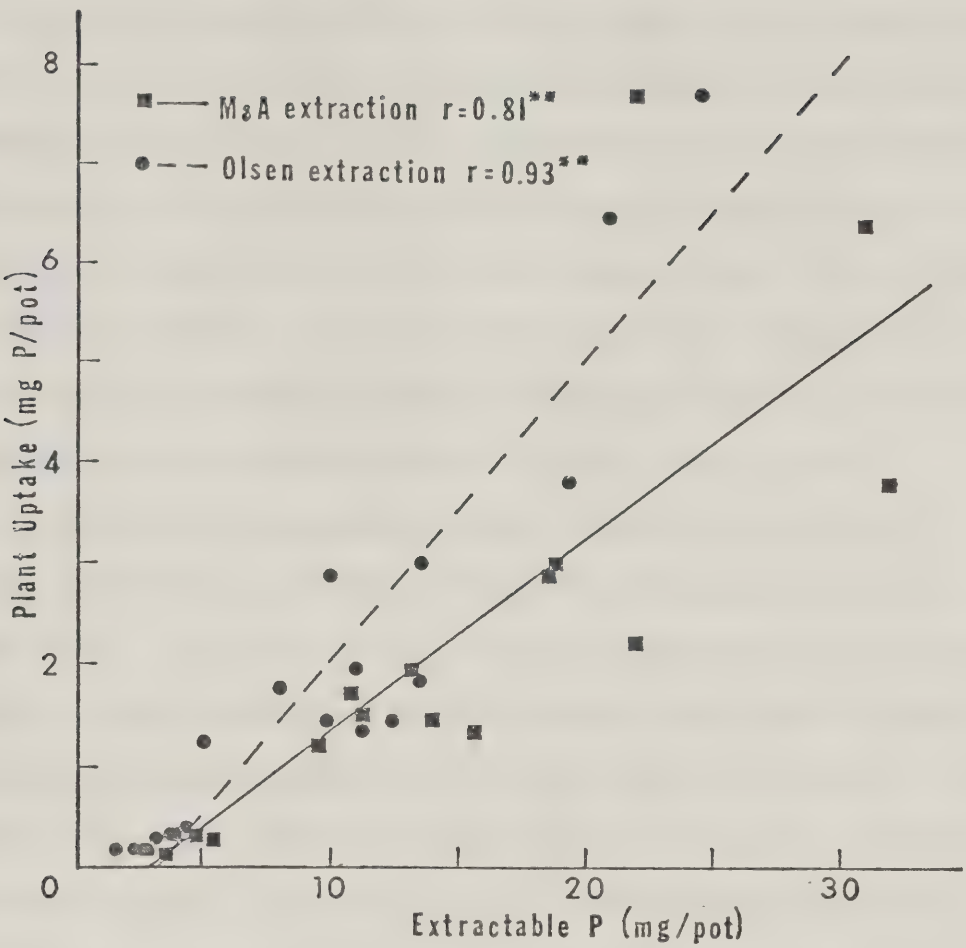



Figure 24 The relationship between P uptake by barley grown in the greenhouse and extractable soil phosphorus by two methods.

## 4.4 Evaluation of Exchangeable Phosphorus

The method by which exchangeable phosphorus is measured is based on equilibrium ratios. The specific activity of solution phosphorus is assumed to be equal to the specific activity of exchangeable phosphorus present in the sample. Therefore the accuracy of the calculation of exchangeable phosphorus is based on the assumption of equilibrium and is controlled by the accuracy of determination of $^{32}P$ specific activity in solution. Determination of $^{32}P$ activity does not present major problems, however determination of phosphorus concentration in solution does. In this study the concentration of phosphorus in equilibium solution for subsoil was often near the limits of detection for the method used. At these levels slight variations in the zero setting, color interference or machine drift could result in relatively large changes in the calculated 'E' value. If for example the true absorbance reading for a sample was 0.02 absorbance units, an error of 0.01 absorbance units could result in an increase in the calculated 'E' value of 33% or a decrease of 50%. It must be remembered that 0.01 absorbance units was equivalent to less than 0.01 ug P/ml of solution. Although there were problems in determining 'E' values for all soil samples, they were not as pronounced for surface soils as subsoils and the results obtained for the 0-15 cm soil samples were reproducible. The relationships between 'E' values and extractable phosphorus for the surface soils are shown in Figures 25 and 26. In all cases

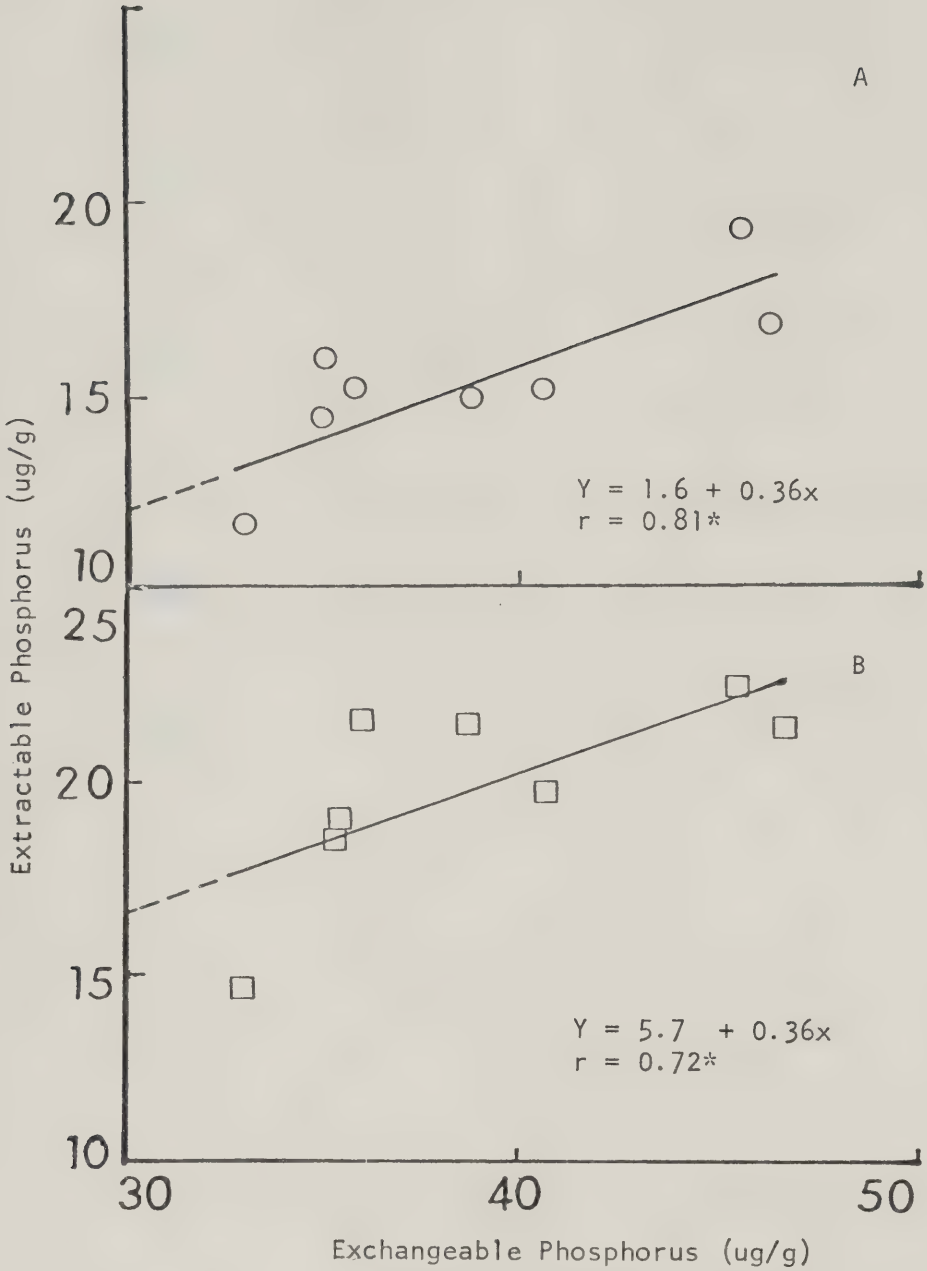



Figure 25 The relationship between exchangeable phosphorus and Olsen extractable phosphorus A and Miller and Axley extractable phosphorus B for the 0-15 cm depth at the 1977 Ellerslie site.

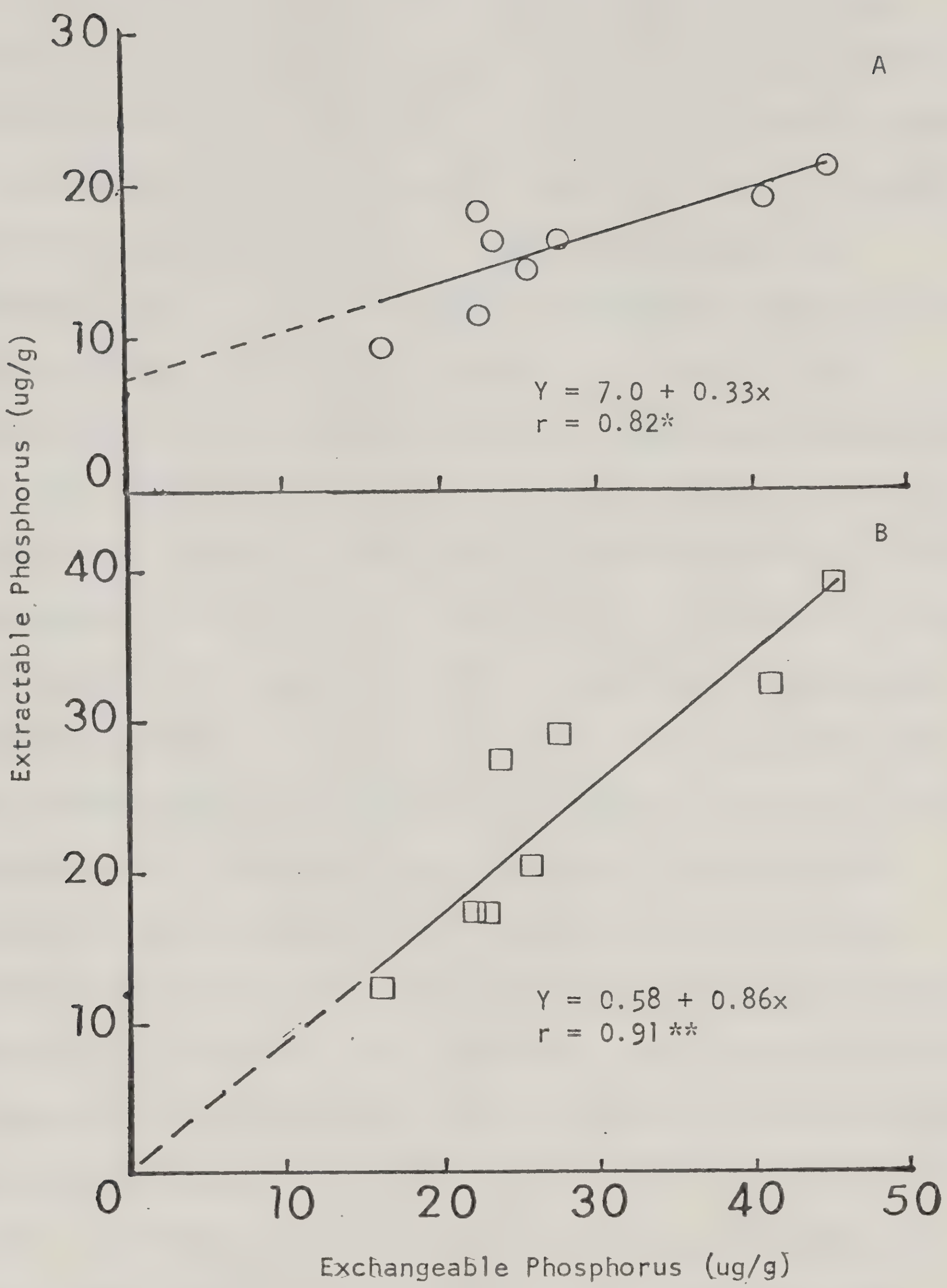



Figure 26 The relationship between exchangeable phosphorus and Olsen extractable phosphorus A and Miller and Axley extractable phosphorus B for the 0-15 cm depth at the 1977 Vegreville site.

the linear correlation of exchangeable phosphorus and extractable phosphorus is significant at $P \leq 0.05$. However the regressions do not intersect the origin as would be expected if the two approaches measured essentially the same form of phosphorus. As no reliable values for exchangeable phosphorus in the subsoil could be obtained using the method A (0.01 M $CaCl_2$ extraction solution), method B ($H_2O$ extraction) was used to study three representative profiles from both the Vegreville and Ellerslie sites. The values obtained are given in Table 14. The data show that for both sites there is a very poor relationship between 'E' values and extractable phosphorus when all profile depths are considered together. It is important to notice that the relationship between exchangeable phosphorus and extractable phosphorus for the subsoil at Ellerslie is reasonably consistent while the subsoil values at Vegreville are extemely variable. This observation is important because it illustrates the degree of variability that might be expected to occur at the Vegreville site. Figures 16 and 17 indicate the high variability in subsoil pH at the Vegreville site and the relatively uniform values at the Ellerslie site. It appears that chemical conditions in the soil may have a decided effect on the relationship between 'E' value and extractable phosphorus. If the 'E' values obtained by method B are considered to be valid measurements of 'E' value for the soils and are used to calculate phosphorus uptake from depth the uptake of phosphorus by barley would have to be

Table 14 Exchangeable P and extractable P for selected profiles from the 1977 plot sites.

| Site | Plot | Depth cm | 'E' Value (ug/g) | M&A (ug/g) | Olsen (ug/g) |
|---|---|---|---|---|---|
| Vegreville | 1-1 | 0-15 | 53 | 29 | 17 |
| | | 15-30 | 59 | 2.8 | 2.4 |
| | | 30-45 | 23 | 6.2 | 7.3 |
| | 2-2 | 0-15 | 45 | 21 | 14 |
| | | 15-30 | 17 | 1.4 | 2.0 |
| | | 30-45 | 32 | 1.0 | 1.5 |
| | 3-1 | 0-15 | 35 | 17 | 12 |
| | | 15-45 | 35 | 2.7 | 1.6 |
| | | 30-45 | 35 | 1.2 | 1.6 |
| Ellerslie | 1-1 | 0-15 | 45 | 18 | 16 |
| | | 15-30 | 17 | 1.6 | 1.6 |
| | | 30-45 | 15 | 2.2 | 1.7 |
| | 2-2 | 0-15 | 47 | 22 | 17 |
| | | 15-30 | 16 | 2.9 | 2.0 |
| | | 30-45 | 22 | 2.9 | 2.6 |
| | 3-1 | 0-15 | 43 | 22 | 15 |
| | | 15-30 | 21 | 2.1 | 1.6 |
| | | 30-45 | 22 | 2.1 | 2.0 |

mainly from the subsoil. The greenhouse study indicates that there is very little phosphorus in the subsoil that is available to barley under greenhouse conditions. It appears that the laboratory determined 'E' values vastly overestimated the readily exchangeable phosphorus present in the subsoil. It is possible that the rates of isotope exchange that occurred in the laboratory determinations of 'E' value were far greater than occur under field conditions for these soils. The results appear to indicate that extractable phosphorus is a better estimation of the amount of phosphorus that is readily exchangeable in the undisturbed soil and for this reason, as well as others mentioned previously, it was decided that it was justifiable to use extractable phosphorus in the calculation of distribution of phosphorus uptake by barley.

## 5. General Discussion and Conclusions

The aim of this investigation was to obtain a measure of the importance of subsoil phosphorus to barley crops in Alberta. The results of the study suggest that the subsoil is not an important source of phosphorus for barley under most conditions. It was found that the maximum contribution of subsoil phosphorus was only 30% of the total phosphorus use by barley and the importance of subsoil phosphorus declined markedly with the addition of phosphorus fertilizer to the Ap horizon. There were no clear effects of moisture on the importance of subsoil phosphorus to barley; however low moisture levels in one part of the root zone appeared to result in relatively more phosphorus being absorbed from other parts of the root zone. The results also suggest that there are several problems with the $^{32}P$ soil injection method. There is a high degree of variability in the values obtained and this complicates evaluation of both the data and the method. Other workers who have used variations of the $^{32}P$ soil injection method have reported that variability was so great as to preclude obtaining statistically significant results (Osman, 1971 and Paasikallio, 1976).

The results from the 1977 field experiments indicate that there may be a fundamental flaw in the method. The results suggest that barley plants do not act as a 'zero sink' for phosphorus and that there may be a considerable 'efflux' of phosphorus out of the plant. The work of Rovira and Bowen (1970) supports this hypothesis. In a study of

intact roots of wheat seedlings they reported that 3.4 % of the $^{32}P$ absorbed by the seedlings in a 15 minute period was found outside of the root after a further one hour period. In their study they were interested in determining rates of absorption over short time periods and considered the loss insignificant. However, losses much less than they reported could be quite significant over the time involved in field experiments such as were carried out in this study. If losses do occur, it severely limits the usefulness of the $^{32}P$ soil injection method for determination of the distribution of phosphorus uptake with respect to depth.

Further problems are encountered in the determination of 'E' values. Although 'E' values are often considered less empirical than chemical extractions, they are in the author's opinion, at least as empirical as chemical extraction methods. Russell *et al*. (1957) state: "all inorganic phosphate fractions in the soil must be regarded as undergoing exchange, although at very different rates." The fact that all soil phosphorus is potentially exchangeable along with the fact that rates of exchange differ widely and are subject to numerous complicating factors (Arambarri and Talibudeen, 1959 a,b,c ; Rennie and Paul, 1971 and Russell *et al*.,1957) results in what the author believes to be an empirical measurement. If it were possible to define all factors affecting the determination of 'E' value in the laboratory the same complicating factors would still apply in the field where control and/or

estimation of factors would be much more difficult. For these reasons the author feels that the value of the $^{32}P$ soil injection method under field conditions is extremely limited.

In conclusion, it appears that there are several difficulties in using the $^{32}P$ soil injection method to study uptake of phosphorus. These must be understood before the method can be used to obtain reliable data on the uptake of phosphorus from different soil compartments. In the author's opinion it is important that the apparent loss of phosphorus from plant roots be studied more thoroughly. If phosphorus does move out of plant roots in significant amounts, it is important that we recognize this because it will affect much of our thinking on phosphorus nutrition of plants.

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# Appendices

# APPENDIX I

## Chemical and Physical Data for Soils from Field Plots

| Site | Depth | pH* | E.C.** | S.A.R. | Total Carbon | $CaCO_3$ Equivalent | Particle-size separates Sand | Silt | Clay | Moisture Content 1/3 bar | 15 bar | Db |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cm | | | | % | % | % | % | % | % | % | $g/cm^3$ |
| Breton | 0-15 | 6.1 | 1.0 | 1.8 | 1.6 | 0.08 | 32 | 41 | 27 | 26.2 | 8.4 | 1.40 |
| (1976) | 15-30 | 6.4 | 0.4 | 0.4 | 0.5 | 0.16 | 30 | 29 | 41 | 26.1 | 12.7 | 1.45 |
| | 30-45 | 6.3 | 0.3 | 0.4 | 0.4 | 0.13 | 29 | 29 | 42 | 27.8 | 14.0 | 1.64 |
| Ellerslie | 0-15 | 6.2 | 0.4 | 0.4 | 5.0 | 0.09 | 29 | 42 | 29 | 33.9 | 17.0 | 1.04 |
| (1976) | 15-30 | 6.4 | 0.4 | 0.4 | 2.2 | 0.09 | 32 | 37 | 31 | 25.9 | 11.4 | 1.22 |
| | 30-45 | 6.3 | 0.3 | 0.4 | 0.9 | 0.08 | 34 | 31 | 35 | 23.2 | 11.1 | 1.46 |
| Vegreville | 0-15 | 6.0 | 1.0 | 6.4 | 3.2 | 0.04 | 17 | 47 | 36 | 36.3 | 15.0 | 1.15 |
| (1976) | 15-30 | 6.5 | 4.2 | 11.9 | 1.4 | 0.06 | 12 | 37 | 51 | 32.4 | 18.0 | 1.48 |
| | 30-45 | 7.3 | 6.5 | 12.6 | 0.9 | 0.6 | 10 | 34 | 56 | 31.8 | 15.2 | 1.44 |
| Ellerslie | 0-15 | 5.7 | 0.3 | 0.3 | 6.2 | 0.0 | 22 | 42 | 36 | 41.2 | 19.2 | 0.93 |
| (1977) | 15-30 | 5.8 | 0.4 | 0.3 | 5.0 | 0.05 | 20 | 43 | 37 | 39.3 | 17.6 | 1.19 |
| | 30-45 | 5.7 | 0.4 | 0.4 | 2.2 | 0.07 | 24 | 38 | 38 | 34.3 | 14.6 | 1.27 |
| Vegreville | 0-15 | 5.5 | 0.8 | 1.7 | 4.5 | 0.05 | 19 | 47 | 34 | 37.5 | 18.2 | 0.98 |
| (1977) | 15-30 | 6.7 | 1.2 | 5.6 | 2.0 | 0.15 | 14 | 44 | 42 | 31.7 | 16.1 | 1.43 |
| | 30-45 | 6.8 | 3.1 | 7.0 | 1.2 | 9.16 | 10 | 38 | 52 | 31.4 | 17.4 | 1.59 |

* Water saturated paste

** Saturation paste extract

APPENDIX I (cont.)

Legal locations for 1976 and 1977 field studies.

| Location | Legal Location |
| --- | --- |
| Breton | NE 25-47-4 W 5 |
| Ellerslie | NE 24-51-25 W 4 |
| Vegreville | NE 29-52-14 W 4 |

# APPENDIX 2

(after Newbould and Taylor 1964)

Calculation of relative and absolute uptake of phosphorus from different depths in the soil.

Variables:

Tp = $^{32}P$ specific activity of plant material

Np = Total P uptake from each compartment*

Ns = Exchangeable soil P in each compartment

Db = Soil bulk density in each compartment

n = The number of compartments from which the plant absorbs phosphorus

Equations 1 and 2 describe the absolute uptake from compartment i and equation 3 describes the relative uptake from compartment i.

$$\frac{Npi}{\sum_{i=1}^{n} Np} = \frac{Tpi \cdot Nsi \cdot Dbi}{\sum_{i=1}^{n} (Tp \cdot Ns \cdot Db)} \qquad (1)$$

$$Npi = \frac{Tpi \cdot Nsi \cdot Dbi}{\sum_{i=1}^{n} (Tp \cdot Ns \cdot Db)} \cdot \sum_{i=1}^{n} Np \qquad (2)$$

$$\%\ \text{uptake } i = 100 \cdot \frac{Tpi \cdot Nsi \cdot Dbi}{\sum_{i=1}^{n} (Tp \cdot Ns \cdot Db)} \qquad (3)$$

* Compartment refers to a 15 cm thickness of soil at a specified depth in the profile. In this study there were three compartments: 0-15 cm, 15-30 cm and 30-45 cm.

APPENDIX 3

Uptake data from 1976 and 1977 field studies.

| Table | Description |
|---|---|
| 3a | Breton 1976 |
| 3b | Ellerslie 1976 |
| 3c | Vegreville 1976 |
| 3d | Ellerslie 1977 |
| 3e | Vegreville 1977 |

Appendix 3a Uptake data for 1976 Breton field study.

| | Treatment♦ | Depth cm | Specific Activity dpm/ug P | Olsen P ppm | M.&A.▲ P ppm | Olsen Uptake P kg/ha | M.&A. Uptake P kg/ha | Olsen Uptake P % | M.&A. Uptake P % |
|---|---|---|---|---|---|---|---|---|---|
| REP-1 | DP1 | 0-15 | 3.04 | 8.3 | 9.4 | 5.78 | 5.60 | 59.1 | 57.4 |
| | | 15-30 | 3.10 | 2.5 | 3.2 | 1.84 | 2.00 | 18.8 | 20.5 |
| | | 30-45 | 2.30 | 3.5 | 4.1 | 2.16 | 2.16 | 22.1 | 22.1 |
| | DP2 | 0-15 | 4.46 | 11.8 | 12.8 | 9.22 | 9.12 | 88.9 | 87.8 |
| | | 15-30 | 0.75 | 2.5 | 3.2 | 0.34 | 0.40 | 3.3 | 3.8 |
| | | 30-45 | 1.13 | 3.5 | 4.1 | 0.82 | 0.87 | 7.9 | 8.4 |
| | IP1 | 0-15 | 3.58 | 8.3 | 9.4 | 7.86 | 7.78 | 82.4 | 81.6 |
| | | 15-30 | 0.68 | 2.5 | 3.2 | 0.47 | 0.52 | 4.9 | 5.4 |
| | | 30-45 | 1.12 | 3.5 | 4.1 | 1.22 | 1.24 | 12.7 | 13.0 |
| | IP2 | 0-15 | 2.25 | 11.75 | 12.8 | 9.84 | 9.65 | 81.6 | 80.0 |
| | | 15-30 | 0.77 | 2.5 | 3.2 | 0.74 | 0.85 | 6.2 | 7.0 |
| | | 30-45 | 0.97 | 3.5 | 4.1 | 1.48 | 1.56 | 12.3 | 13.0 |
| REP-2 | DP1 | 0-15 | 1.96 | 15.2 | 18.3 | 8.90 | 8.97 | 77.2 | 77.9 |
| | | 15-30 | 1.06 | 3.2 | 4.0 | 1.07 | 1.10 | 9.3 | 9.5 |
| | | 30-45 | 1.46 | 3.1 | 3.4 | 1.56 | 1.45 | 13.5 | 12.6 |
| | DP2 | 0-15 | 2.16 | 16.5 | 22.6 | 11.8 | 12.0 | 89.9 | 91.3 |
| | | 15-30 | 0.50 | 3.2 | 4.0 | 0.56 | 0.51 | 4.2 | 3.9 |
| | | 30-45 | 0.65 | 3.1 | 3.4 | 0.76 | 0.64 | 5.9 | 4.8 |
| | IP1 | 0-15 | 2.58 | 15.2 | 18.3 | 9.53 | 9.58 | 87.4 | 87.9 |
| | | 15-30 | 0.54 | 3.2 | 4.0 | 0.44 | 0.45 | 4.1 | 4.2 |
| | | 30-45 | 1.08 | 3.1 | 3.4 | 0.94 | 0.87 | 8.6 | 8.0 |
| | IP2 | 0-15 | 1.52 | 16.5 | 22.6 | 9.72 | 9.87 | 88.6 | 90.0 |
| | | 15-30 | 0.52 | 3.2 | 4.0 | 0.68 | 0.62 | 6.2 | 5.6 |
| | | 30-45 | 0.42 | 3.1 | 3.4 | 0.58 | 0.48 | 5.3 | 4.4 |
| REP-3 | DP1 | 0-15 | 3.49 | 14.6 | 15.0 | 7.72 | 7.58 | 90.2 | 88.6 |
| | | 15-30 | 1.09 | 2.2 | 3.1 | 0.38 | 0.51 | 4.4 | 6.0 |
| | | 30-45 | 0.63 | 4.1 | 4.4 | 0.46 | 0.47 | 5.4 | 5.5 |
| | DP2 | 0-15 | 1.79 | 22.6 | 21.2 | 10.6 | 10.1 | 89.1 | 85.2 |
| | | 15-30 | 1.66 | 2.2 | 3.1 | 0.99 | 1.43 | 8.3 | 12.1 |
| | | 30-45 | 0.24 | 4.1 | 4.4 | 0.30 | 0.33 | 2.6 | 2.8 |
| | IP1 | 0-15 | 0.16 | 14.6 | 15.0 | 4.14 | 3.55 | 39.7 | 34.1 |
| | | 15-30 | 1.07 | 2.2 | 3.1 | 4.30 | 5.12 | 41.3 | 49.2 |
| | | 30-45 | 0.23 | 4.1 | 4.4 | 1.97 | 1.74 | 19.0 | 16.7 |
| | IP2 | 0-15 | 1.20 | 22.6 | 21.2 | 9.14 | 8.83 | 76.4 | 73.8 |
| | | 15-30 | 0.27 | 2.2 | 3.1 | 0.21 | 0.30 | 1.7 | 2.5 |
| | | 30-45 | 1.60 | 4.1 | 4.4 | 2.62 | 2.84 | 21.7 | 23.7 |

▲ M.&A. refers to the Miller and Axley extraction method.

♦ D = non-irrigated (natural moisture conditions)

I = irrigated (5 cm additional moisture in 2 applications)

P1= 10 kg phosphorus/ha prior to seeding

P2= 40 kg phosphorus/ha prior to seeding

Appendix 3b Uptake data for 1976 Ellerslie field study.

| | Treatment♦ | Depth cm | Specific Activity dpm/ug P | Olsen P ppm | M.&A.▲ P ppm | Olsen Uptake P kg/ha | M.&A. Uptake P kg/ha | Olsen Uptake P % | M.&A. Uptake P % |
|---|---|---|---|---|---|---|---|---|---|
| REP-1 | DP1 | 0-15 | 3.94 | 7.8 | 8.1 | 8.68 | 7.47 | 87.8 | 75.5 |
| | | 15-30 | 1.94 | 0.9 | 2.4 | 0.58 | 1.28 | 5.9 | 12.9 |
| | | 30-45 | 2.12 | 0.75 | 1.64 | 0.63 | 1.14 | 6.4 | 11.6 |
| | DP2 | 0-15 | 1.57 | 11.1 | 11.8 | 12.8 | 11.4 | 91.3 | 81.4 |
| | | 15-30 | 1.23 | 0.9 | 2.4 | 0.95 | 2.13 | 6.8 | 15.2 |
| | | 30-45 | 0.34 | 0.75 | 1.64 | 0.26 | 0.48 | 1.9 | 3.4 |
| | IP1 | 0-15 | 2.51 | 7.8 | 8.1 | 8.93 | 7.94 | 91.5 | 81.4 |
| | | 15-30 | 1.30 | 0.9 | 2.4 | 0.63 | 1.43 | 6.4 | 14.7 |
| | | 30-45 | 0.43 | 0.75 | 1.64 | 0.21 | 0.39 | 2.1 | 4.0 |
| | IP2 | 0-15 | 1.47 | 11.1 | 11.8 | 12.4 | 11.5 | 93.9 | 87.1 |
| | | 15-30 | 0.53 | 0.9 | 2.4 | 0.43 | 0.99 | 3.2 | 7.5 |
| | | 30-45 | 0.47 | 0.75 | 1.64 | 0.38 | 0.72 | 2.9 | 5.4 |
| REP-2 | DP1 | 0-15 | 2.39 | 1[illegible].5 | 12.8 | 9.20 | 8.92 | 71.2 | 69.1 |
| | | 15-30 | 1.07 | 4.2 | 5.9 | 1.76 | 2.15 | 13.7 | 16.6 |
| | | 30-45 | 1.17 | 3.5 | 3.8 | 1.95 | 1.84 | 15.1 | 14.3 |
| | DP2 | 0-15 | 1.44 | 16.6 | 14.2 | 10.1 | 8.83 | 74.1 | 64.9 |
| | | 15-30 | 1.31 | 4.2 | 5.9 | 2.72 | 3.89 | 20.0 | 25.6 |
| | | 30-45 | 0.38 | 3.5 | 3.8 | 0.80 | 0.89 | 5.9 | 6.5 |
| | IP1 | 0-15 | 1.46 | 11.5 | 12.8 | 8.01 | 7.63 | 66.4 | 63.2 |
| | | 15-30 | 1.08 | 4.2 | 5.9 | 2.54 | 3.03 | 21.0 | 25.1 |
| | | 30-45 | 0.64 | 3.5 | 3.8 | 1.52 | 1.41 | 12.6 | 11.7 |
| | IP2 | 0-15 | 1.18 | 16.6 | 14.2 | 12.2 | 11.0 | 78.0 | 70.2 |
| | | 15-30 | 0.71 | 4.2 | 5.9 | 2.17 | 3.20 | 13.9 | 20.5 |
| | | 30-45 | 0.41 | 3.5 | 3.8 | 1.27 | 1.45 | 8.1 | 9.3 |
| REP-3 | DP1 | 0-15 | 2.95 | 10.1 | 12.2 | 9.67 | 8.87 | 85.4 | 78.4 |
| | | 15-30 | 2.01 | 1.65 | 3.4 | 1.26 | 1.97 | 11.2 | 17.4 |
| | | 30-45 | 0.70 | 1.2 | 2.0 | 0.39 | 0.48 | 3.4 | 4.3 |
| | DP2 | 0-15 | 1.97 | 16.8 | 15.4 | 10.7 | 10.2 | 92.0 | 85.0 |
| | | 15-30 | 0.77 | 1.65 | 3.4 | 0.48 | 1.03 | 4.1 | 8.6 |
| | | 30-45 | 0.82 | 1.2 | 2.0 | 0.45 | 0.77 | 3.8 | 6.4 |
| | IP1 | 0-15 | 0.96 | 10.1 | 12.2 | 7.85 | 6.55 | 65.7 | 54.8 |
| | | 15-30 | 1.70 | 1.65 | 3.4 | 2.66 | 3.78 | 22.3 | 31.6 |
| | | 30-45 | 1.04 | 1.2 | 2.0 | 1.44 | 1.62 | 12.1 | 13.6 |
| | IP2 | 0-15 | 0.93 | 16.8 | 15.4 | 9.81 | 8.26 | 79.8 | 67.1 |
| | | 15-30 | 0.57 | 1.65 | 3.4 | 0.69 | 1.31 | 5.6 | 10.6 |
| | | 30-45 | 1.70 | 1.2 | 2.0 | 1.80 | 2.74 | 14.6 | 22.3 |

▲ M.&A. refers to the Miller and Axley extraction method.

♦ D = non-irrigated (natural moisture conditions)
I = irrigated (5 cm additional moisture in 2 applications)
P1= 10 kg phosphorus/ha prior to seeding
P2= 40 kg phosphorus/ha prior to seeding

Appendix 3c Uptake data for 1976 Vegreville field study.

| | Treatment ♦ | Depth cm | Specific Activity dpm/ug P | Olsen P ppm | M.&A.▲ P ppm | Olsen Uptake P kg/ha | M.&A. Uptake P kg/ha | Olsen Uptake P % | M.&A. Uptake P % |
|---|---|---|---|---|---|---|---|---|---|
| REP-1 | DP1 | 0-15 | 2.61 | 4.85 | 9.5 | 3.82 | 5.51 | 44.1 | 63.6 |
| | | 15-30 | 1.22 | 1.85 | 2.4 | 0.88 | 0.84 | 10.1 | 9.7 |
| | | 30-45 | 4.47 | 2.35 | 1.85 | 3.97 | 2.31 | 45.8 | 26.7 |
| | DP2 | 0-15 | 1.54 | 8.7 | 15.1 | 8.73 | 10.4 | 63.0 | 74.8 |
| | | 15-30 | 1.37 | 1.85 | 2.4 | 2.14 | 1.89 | 15.4 | 13.6 |
| | | 30-45 | 1.55 | 2.35 | 1.85 | 3.0 | 1.60 | 21.6 | 11.6 |
| | IP1 | 0-15 | 1.68 | 4.85 | 9.5 | 5.43 | 7.0 | 52.5 | 67.7 |
| | | 15-30 | 1.47 | 1.85 | 2.4 | 2.33 | 2.0 | 22.5 | 19.3 |
| | | 30-45 | 1.32 | 2.35 | 1.85 | 2.59 | 1.35 | 25.0 | 13.0 |
| | IP2 | 0-15 | 1.09 | 8.7 | 15.1 | 9.5 | 10.7 | 71.2 | 80.5 |
| | | 15-30 | 0.81 | 1.85 | 2.4 | 1.94 | 1.63 | 14.6 | 12.2 |
| | | 30-45 | 0.64 | 2.35 | 1.85 | 1.9 | 0.97 | 14.2 | 7.3 |
| REP-2 | DP1 | 0-15 | 2.43 | 10.8 | 17.9 | 6.17 | 6.46 | 83.4 | 87.4 |
| | | 15-30 | 1.82 | 1.85 | 2.4 | 1.02 | 0.83 | 13.9 | 11.3 |
| | | 30-45 | 0.29 | 2.35 | 1.85 | 0.20 | 0.10 | 2.7 | 1.4 |
| | DP2 | 0-15 | 1.32 | 12.9 | 21.9 | 7.99 | 8.73 | 72.4 | 79.0 |
| | | 15-30 | 2.10 | 1.85 | 2.4 | 2.34 | 1.96 | 21.3 | 17.7 |
| | | 30-45 | 0.51 | 2.35 | 1.85 | 0.70 | 0.36 | 6.4 | 3.2 |
| | IP1 | 0-15 | 1.89 | 10.8 | 17.9 | 5.26 | 5.87 | 70.7 | 78.8 |
| | | 15-30 | 2.01 | 1.85 | 2.4 | 1.24 | 1.08 | 16.7 | 14.5 |
| | | 30-45 | 1.24 | 2.35 | 1.85 | 0.95 | 0.50 | 12.7 | 6.7 |
| | IP2 | 0-15 | 1.01 | 12.9 | 21.9 | 7.78 | 8.59 | 76.4 | 84.4 |
| | | 15-30 | 0.75 | 1.85 | 2.4 | 1.08 | 0.91 | 10.6 | 9.0 |
| | | 30-45 | 0.75 | 2.35 | 1.85 | 1.32 | 0.67 | 13.0 | 6.6 |
| REP-3 | DP1 | 0-15 | 0.97 | 10.4 | 13.4 | 3.45 | 3.76 | 45.6 | 49.7 |
| | | 15-45 | 3.0 | 1.85 | 2.4 | 2.45 | 2.69 | 32.3 | 35.5 |
| | | 30-45 | 1.67 | 2.35 | 1.85 | 1.68 | 1.12 | 22.2 | 14.8 |
| | DP2 | 0-15 | 0.82 | 14.4 | 14.9 | 7.05 | 7.42 | 61.2 | 64.4 |
| | | 15-30 | 0.70 | 1.85 | 2.4 | 1.00 | 1.31 | 8.6 | 11.4 |
| | | 30-45 | 1.98 | 2.35 | 1.85 | 3.48 | 2.79 | 30.2 | 24.2 |
| | IP1 | 0-15 | 2.18 | 10.4 | 13.4 | 5.61 | 5.94 | 72.5 | 76.7 |
| | | 15-30 | 1.71 | 1.85 | 2.4 | 1.00 | 1.08 | 13.0 | 13.9 |
| | | 30-45 | 1.54 | 2.35 | 1.85 | 1.12 | 0.73 | 14.5 | 9.4 |
| | IP2 | 0-15 | 1.44 | 14.4 | 14.9 | 9.29 | 9.36 | 85.6 | 86.3 |
| | | 15-30 | 0.54 | 1.85 | 2.4 | 0.58 | 0.73 | 5.3 | 6.7 |
| | | 30-45 | 0.75 | 2.35 | 1.85 | 0.99 | 0.76 | 9.1 | 7.0 |

▲ M.&A. refers to the Miller and Axley extraction method.

♦ D = non-irrigated (natural moisture conditions)
I = irrigated (5 cm additional moisture in 2 applications)
P1= 10 kg phosphorus/ha prior to seeding
P2= 40 kg phosphorus/ha prior to seeding

Appendix 3d Uptake data for 1977 Ellerslie field study.

| | Harvest Date week | Depth cm | Specific Activity dpm/400ug P | Olsen P ppm | M.&A.▲ P ppm | Olsen Uptake P kg/ha | M.&A. Uptake P kg/ha | Olsen Uptake P % | M.&A. Uptake P % |
|---|---|---|---|---|---|---|---|---|---|
| REP-1 | 3 | 0-15 | 7480 | 16.4 | 18.7 | 2.85 | 2.87 | 95.1 | 95.8 |
| | | 15-30 | 2868 | 1.7 | 1.7 | 0.15 | 0.13 | 4.9 | 4.2 |
| | 6 | 0-15 | 3807 | 16.7 | 19.8 | 4.73 | 4.78 | 83.7 | 84.6 |
| | | 15-30 | 4004 | 1.8 | 1.9 | 0.68 | 0.60 | 12.1 | 10.6 |
| | | 30-45 | 1685 | 1.4 | 1.8 | 0.24 | 0.27 | 4.2 | 4.7 |
| | 8 | 0-15 | 1610 | 16.4 | 18.6 | 7.42 | 7.45 | 81.7 | 82.1 |
| | | 15-30 | 2645 | 1.6 | 1.7 | 1.53 | 1.46 | 16.8 | 16.1 |
| | | 30-45 | 248 | 1.4 | 2.0 | 0.14 | 0.16 | 1.5 | 1.8 |
| REP-2 | 3 | 0-15 | 12850 | 14.2 | 17.1 | 2.16 | 2.17 | 94.6 | 95.3 |
| | | 15-30 | 4254 | 1.9 | 2.0 | 0.12 | 0.11 | 5.4 | 4.7 |
| | 6 | 0-15 | 5596 | 14.6 | 17.7 | 5.29 | 5.28 | 93.1 | 92.9 |
| | | 15-30 | 1518 | 1.6 | 1.8 | 0.20 | 0.19 | 3.6 | 3.3 |
| | | 30-45 | 1584 | 1.3 | 1.9 | 0.19 | 0.22 | 3.3 | 3.8 |
| | 8 | 0-15 | 2848 | 12.5 | 15.2 | 7.41 | 7.47 | 86.1 | 86.8 |
| | | 15-30 | 1791 | 1.8 | 1.9 | 0.86 | 0.77 | 10.0 | 8.9 |
| | | 30-45 | 814 | 1.4 | 2.0 | 0.34 | 0.37 | 3.9 | 4.3 |
| REP-3 | 3 | 0-15 | 7754 | 13.1 | 17.4 | 2.83 | 2.85 | 95.2 | 95.7 |
| | | 15-30 | 2833 | 1.4 | 1.7 | 0.14 | 0.13 | 4.8 | 4.3 |
| | 6 | 0-15 | 4785 | 14.4 | 18.0 | 6.09 | 6.12 | 90.1 | 90.5 |
| | | 15-30 | 3183 | 1.5 | 1.8 | 0.54 | 0.51 | 8.0 | 7.5 |
| | | 30-45 | 808 | 1.3 | 1.7 | 0.13 | 0.14 | 1.4 | 2.0 |
| | 8 | 0-15 | 2178 | 14.8 | 19.8 | 8.33 | 8.45 | 89.8 | 91.1 |
| | | 15-30 | 1670 | 1.5 | 1.7 | 0.83 | 0.71 | 8.9 | 7.7 |
| | | 30-45 | 226 | 1.5 | 1.8 | 0.12 | 0.11 | 1.3 | 1.2 |

▲ M.&A. refers to the Miller and Axley extraction method.

Appendix 3e Uptake data for 1977 Vegreville field study.

| | Harvest Date week | Depth cm | Specific Activity dpm/400ug P | Olsen P ppm | M.&A.▲ P ppm | Olsen Uptake P kg/ha | M.&A. Uptake P kg/ha | Olsen Uptake P % | M.&A. Uptake P % |
|---|---|---|---|---|---|---|---|---|---|
| REP-1 | 4 | 0-15 | 5980 | 15.4 | 23.1 | 3.63 | 3.74 | 85.7 | 88.2 |
| | | 15-30 | 5590 | 1.9 | 2.3 | 0.60 | 0.50 | 14.3 | 11.9 |
| | 6 | 0-15 | 1834 | 14.5 | 19.4 | 8.95 | 9.01 | 89.1 | 89.7 |
| | | 15-30 | 1020 | 1.3 | 1.6 | 0.66 | 0.78 | 6.5 | 7.8 |
| | | 30-45 | 282 | 2.9 | 2.2 | 0.44 | 0.26 | 4.4 | 2.5 |
| | 8 | 0-15 | 385 | 18.2 | 29.1 | 7.81 | 8.63 | 70.6 | 78.0 |
| | | 15-30 | 626 | 2.3 | 2.7 | 2.31 | 1.92 | 20.9 | 17.4 |
| | | 30-45 | 95 | 5.4 | 4.3 | 0.94 | 0.52 | 8.9 | 4.6 |
| REP-2 | 4 | 0-15 | 12460 | 13.9 | 16.5 | 5.49 | 5.47 | 94.3 | 93.9 |
| | | 15-30 | 5145 | 1.4 | 1.8 | 0.33 | 0.36 | 5.7 | 6.1 |
| | 6 | 0-15 | 3112 | 14.8 | 20.7 | 8.18 | 8.53 | 80.9 | 84.2 |
| | | 15-30 | 2338 | 1.7 | 1.7 | 1.05 | 0.79 | 10.4 | 7.8 |
| | | 30-45 | 1819 | 1.7 | 2.1 | 0.88 | 0.81 | 8.7 | 8.0 |
| | 8 | 0-15 | 996 | 12.4 | 14.9 | 10.1 | 10.8 | 74.2 | 79.6 |
| | | 15-30 | 934 | 1.7 | 1.6 | 1.9 | 1.6 | 14.1 | 11.6 |
| | | 30-45 | 434 | 2.8 | 2.3 | 1.6 | 1.2 | 11.8 | 8.8 |
| REP-3 | 4 | 0-15 | 4895 | 16.7 | 25.5 | 5.73 | 5.75 | 95.8 | 96.1 |
| | | 15-30 | 1620 | 2.2 | 2.1 | 0.25 | 0.23 | 4.2 | 3.9 |
| | 6 | 0-15 | 1214 | 14.7 | 22.2 | 8.92 | 9.29 | 86.8 | 90.4 |
| | | 15-30 | 637 | 2.5 | 1.9 | 0.79 | 0.60 | 7.7 | 5.9 |
| | | 30-45 | 413 | 2.7 | 1.6 | 0.56 | 0.38 | 5.5 | 3.7 |
| | 8 | 0-15 | 369 | 14.6 | 23.3 | 8.54 | 9.37 | 70.7 | 77.6 |
| | | 15-30 | 458 | 2.6 | 2.3 | 1.92 | 1.70 | 15.9 | 14.1 |
| | | 30-45 | 454 | 2.3 | 1.3 | 1.62 | 1.01 | 13.4 | 8.3 |

▲ M.&A. refers to the Miller and Axley extraction method.

# APPENDIX 4

Phosphorus Sorption curves for 1977 greenhouse soils.

| Soil | Depth | Final Solution (ug P/ml) | P sorption (ug P/g) |
|---|---|---|---|
| Breton | 0-15 | 0.18 | -1.9 |
| | | 0.30 | 3.9 |
| | | 0.58 | 8.3 |
| | 15-30 | 0.06 | 8.6 |
| | | 0.12 | 17.5 |
| | | 0.54 | 40 |
| | | 1.7 | 67 |
| | 30-45 | 0.06 | 8.6 |
| | | 0.10 | 18 |
| | | 0.93 | 32 |
| | | 1.6 | 70 |
| Ellerslie | 0-15 | 0.17 | -1.8 |
| | | 0.29 | 4.0 |
| | | 0.47 | 11 |
| | | 2.7 | 45 |
| | 15-30 | 0.05 | 8.9 |
| | | 0.08 | 18 |
| | | 0.37 | 43 |
| | | 1.3 | 74 |
| | 30-45 | 0.05 | 19 |
| | | 1.0 | 78 |
| | | 2.2 | 100 |
| Vegreville | 0-15 | 0.15 | -1.4 |
| | | 0.27 | 4.5 |
| | | 0.50 | 9.9 |
| | 15-30 | 0.14 | 48 |
| | | 0.47 | 92 |
| | | 1.2 | 125 |
| | | 2.3 | 160 |
| | 30-45 | 0.27 | 94 |
| | | 0.78 | 130 |
| | | 1.4 | 170 |